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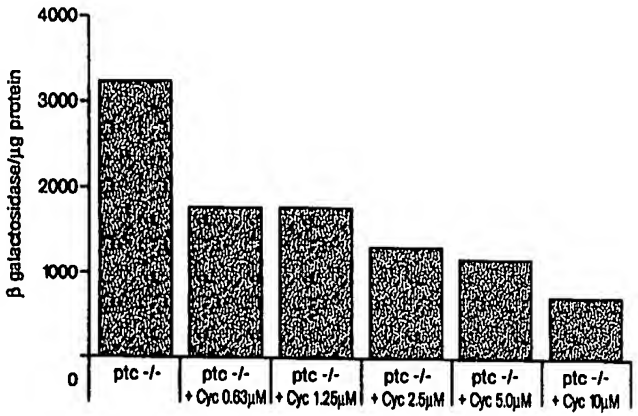

(57) Abstract

The present invention makes available assays and reagents inhibiting paracrine and/or autocrine signals produced by a hedgehog protein or aberrant activation of a hedgehog signal transduction pathway, e.g., which involve the use of a steroidal alkaloid or other small molecule.

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USE OF STEROIDAL ALKALOID DERIVATIVES AS INHIBITORS OF HEDGEHOG SIGNALING PATHWAYS

Background of the Invention

Pattern formation is the activity by which embryonic cells form ordered spatial arrangements of differentiated tissues. The physical complexity of higher organisms arises during embryogenesis through the interplay of cell-intrinsic lineage and cell-extrinsic signaling. Inductive interactions are essential to embryonic patterning in vertebrate development from the earliest establishment of the body plan, to the patterning of the organ systems, to the generation of diverse cell types during tissue differentiation (Davidson, E., (1990) Development 108: 365-389; Gurdon, J. B., (1992) Cell 68: 185-199; Jessell, T. M. et al., (1992) Cell 68: 257-270). The effects of developmental cell interactions are varied. Typically, responding cells are diverted from one route of cell differentiation to another by inducing cells that differ from both the uninduced and induced states of the responding cells (inductions). Sometimes cells induce their neighbors to differentiate like themselves (homeogenetic induction); in other cases a cell inhibits its neighbors from differentiating like itself. Cell interactions in early development may be sequential, such that an initial induction between two cell types leads to a progressive amplification of diversity. Moreover, inductive interactions occur not only in embryos, but in adult cells as well, and can act to establish and maintain morphogenetic patterns as well as induce differentiation (J.B. Gurdon (1992) Cell 68:185-199).

Members of the *Hedgehog* family of signaling molecules mediate many important short- and long-range patterning processes during invertebrate and vertebrate development. In the fly a single *hedgehog* gene regulates segmental and imaginal disc patterning. In contrast, in vertebrates a *hedgehog* gene family is involved in the control of left-right asymmetry, polarity in the CNS, somites and limb, organogenesis, chondrogenesis and spermatogenesis.

The first *hedgehog* gene was identified by a genetic screen in the fruitfly *Drosophila melanogaster* (Nüsslein-Volhard, C. and Wieschaus, E. (1980) Nature 287, 795-801). This screen identified a number of mutations affecting embryonic and larval development. In 1992 and 1993, the molecular nature of the *Drosophila hedgehog* (*hh*) gene was reported (*C.F.*, Lee et al. (1992) Cell 71, 33-50), and since then, several *hedgehog* homologues have been isolated from various vertebrate species. While only one *hedgehog* gene has been found in *Drosophila* and other invertebrates, multiple *Hedgehog* genes are present in vertebrates.

The various Hedgehog proteins consist of a signal peptide, a highly conserved N-terminal region, and a more divergent C-terminal domain. In addition to signal sequence cleavage in the secretory pathway (Lee, J.J. et al. (1992) Cell 71:33-50; Tabata, T. *et al.* (1992) Genes Dev. 2635-2645; Chang, D.E. *et al.* (1994) Development 120:3339-3353), Hedgehog precursor proteins undergo an internal autoproteolytic cleavage which depends on conserved sequences in the C-terminal portion (Lee *et al.* (1994) Science 266:1528-1537; Porter *et al.* (1995) Nature 374:363-366). This autocleavage leads to a 19 kD N-terminal peptide and a C-terminal peptide of 26-28 kD (Lee *et al.* (1992) supra; Tabata *et al.* (1992) supra; Chang *et al.* (1994) supra; Lee *et al.* (1994) supra; Bumcrot, D.A., *et al.* (1995) Mol. Cell. Biol. 15:2294-2303; Porter *et al.* (1995) supra; Ekker, S.C. *et al.* (1995) Curr. Biol. 5:944-955; Lai, C.J. *et al.* (1995) Development 121:2349-2360). The N-terminal peptide stays tightly associated with the surface of cells in which it was synthesized, while the C-terminal peptide is freely diffusible both *in vitro* and *in vivo* (Porter et al. (1995) Nature 374:363; Lee *et al.* (1994) supra; Bumcrot *et al.* (1995) supra; Mart', E. *et al.* (1995) Development 121:2537-2547; Roelink, H. *et al.* (1995) Cell 81:445-455). Interestingly, cell surface retention of the N-terminal peptide is dependent on autocleavage, as a truncated form of HH encoded by an RNA which terminates precisely at the normal position of internal cleavage is diffusible *in vitro* (Porter *et al.* (1995) supra) and *in vivo* (Porter, J.A. *et al.* (1996) Cell 86, 21-34). Biochemical studies have shown that the autoproteolytic cleavage of the HH precursor protein proceeds through an internal thioester intermediate which subsequently is cleaved in a nucleophilic substitution. It is likely that the nucleophile is a small lipophilic molecule which becomes covalently bound to the C-terminal end of the N-peptide (Porter *et al.* (1996) supra), tethering it to the cell surface. The biological implications are profound. As a result of the tethering, a high local concentration of N-terminal Hedgehog peptide is generated on the surface of the Hedgehog producing cells. It is this N-terminal peptide which is both necessary and sufficient for short and long range Hedgehog signaling activities in *Drosophila* and vertebrates (Porter *et al.* (1995) supra; Ekker *et al.* (1995) supra; Lai *et al.* (1995) supra; Roelink, H. *et al.* (1995) Cell 81:445-455; Porter *et al.* (1996) supra; Fietz, M.J. *et al.* (1995) Curr. Biol. 5:643-651; Fan, C.-M. *et al.* (1995) Cell 81:457-465; Mart', E., *et al.* (1995) Nature 375:322-325; Lopez-Martinez *et al.* (1995) Curr. Biol 5:791-795; Ekker, S.C. *et al.* (1995) Development 121:2337-2347; Forbes, A.J. *et al.*(1996) Development 122:1125-1135).

HH has been implicated in short- and longe range patterning processes at various sites during *Drosophila* development. In the establishment of segment polarity in early embryos, it has short range effects which appear to be directly mediated, while in the

patterning of the imaginal discs, it induces long range effects via the induction of secondary signals.

In vertebrates, several *hedgehog* genes have been cloned in the past few years. Of these genes, *Shh* has received most of the experimental attention, as it is expressed in different organizing centers which are the sources of signals that pattern neighbouring tissues. Recent evidence indicates that *Shh* is involved in these interactions.

The expression of *Shh* starts shortly after the onset of gastrulation in the presumptive midline mesoderm, the node in the mouse (Chang *et al.* (1994) supra; Echelard, Y. *et al.* (1993) Cell 75:1417-1430), the rat (Roelink, H. *et al.* (1994) Cell 76:761-775) and the chick (Riddle, R.D. *et al.* (1993) Cell 75:1401-1416), and the shield in the zebrafish (Ekker *et al.* (1995) supra; Krauss, S. *et al.*(1993) Cell 75:1431-1444). In chick embyros, the *Shh* expression pattern in the node develops a left-right asymmetry, which appears to be responsible for the left-right situs of the heart (Levin, M. *et al.* (1995) Cell 82:803-814).

In the CNS, *Shh* from the notochord and the floorplate appears to induce ventral cell fates. When ectopically expressed, *Shh* leads to a ventralization of large regions of the mid- and hindbrain in mouse (Echelard *et al.* (1993) supra; Goodrich, L.V. *et al.* (1996) Genes Dev. 10:301-312), *Xenopus* (Roelink, H. et al. (1994) *supra*; Ruiz i Altaba, A. *et al.* (1995) Mol. Cell. Neurosci. 6:106-121), and zebrafish (Ekker *et al.* (1995) supra; Krauss *et al.* (1993) supra; Hammerschmidt, M., *et al.* (1996) Genes Dev. 10:647-658). In explants of intermediate neuroectoderm at spinal cord levels, *Shh* protein induces floorplate and motor neuron development with distinct concentration thresholds, floor plate at high and motor neurons at lower concentrations (Roelink *et al.* (1995) supra; Mart' *et al.* (1995) supra; Tanabe, Y. *et al.* (1995) Curr. Biol. 5:651-658). Moreover, antibody blocking suggests that *Shh* produced by the notochord is required for notochord mediated induction of motor neuron fates (Mart' *et al.* (1995) supra). Thus, high concentration of *Shh* on the surface of *Shh*-producing midline cells appears to account for the contact-mediated induction of floorplate observed *in vitro* (Placzek, M. *et al.* (1993) Development 117:205-218), and the midline positioning of the floorplate immediately above the notochord *in vivo*. Lower concentrations of *Shh* released from the notochord and the floorplate presumably induce motor neurons at more distant ventrolateral regions in a process that has been shown to be contact-independent *in vitro* (Yamada, T. *et al.* (1993) Cell 73:673-686). In explants taken at midbrain and forebrain levels, *Shh* also induces the appropriate ventrolateral neuronal cell types, dopaminergic (Heynes, M. *et al.* (1995) Neuron 15:35-44; Wang, M.Z. *et al.* (1995) Nature Med. 1:1184-1188) and cholinergic (Ericson, J. *et al.* (1995) Cell 81:747-756) precursors, respectively, indicating that *Shh* is a

common inducer of ventral specification over the entire length of the CNS. These observations raise a question as to how the differential response to *Shh* is regulated at particular anteroposterior positions.

Shh from the midline also patterns the paraxial regions of the vertebrate embryo, the somites in the trunk (Fan *et al.* (1995) supra) and the head mesenchyme rostral of the somites (Hammerschmidt *et al.* (1996) supra). In chick and mouse paraxial mesoderm explants, *Shh* promotes the expression of sclerotome specific markers like *Pax1* and *Twist*, at the expense of the dermamyotomal marker *Pax3*. Moreover, filter barrier experiments suggest that *Shh* mediates the induction of the sclerotome directly rather than by activation of a secondary signaling mechanism (Fan, C.-M. and Tessier-Lavigne, M. (1994) Cell 79, 1175-1186).

Shh also induces myotomal gene expression (Hammerschmidt et al. (1996) supra; Johnson, R.L. *et al.* (1994) Cell 79:1165-1173; Münsterberg, A.E. *et al.* (1995) Genes Dev. 9:2911-2922; Weinberg, E.S. *et al.* (1996) Development 122:271-280), although recent experiments indicate that members of the WNT family, vertebrate homologues of *Drosophila wingless*, are required in concert (Münsterberg *et al.* (1995) supra). Puzzlingly, myotomal induction in chick requires higher *Shh* concentrations than the induction of sclerotomal markers (Münsterberg *et al.* (1995) supra), although the sclerotome originates from somitic cells positioned much closer to the notochord. Similar results were obtained in the zebrafish, where high concentrations of Hedgehog induce myotomal and repress sclerotomal marker gene expression (Hammerschmidt *et al.* (1996) supra). In contrast to amniotes, however, these observations are consistent with the architecture of the fish embryo, as here, the myotome is the predominant and more axial component of the somites. Thus, modulation of *Shh* signaling and the acquisition of new signaling factors may have modified the somite structure during vertebrate evolution.

In the vertebrate limb buds, a subset of posterior mesenchymal cells, the "Zone of polarizing activity" (ZPA), regulates anteroposterior digit identity (reviewed in Honig, L.S. (1981) Nature 291:72-73). Ectopic expression of *Shh* or application of beads soaked in *Shh* peptide mimics the affect of anterior ZPA grafts, generating a mirror image duplication of digits (Chang *et al.* (1994) supra; Lopez-Martinez *et al.* (1995) *supra*; Riddle *et al.* (1993) supra) (Fig. 2g). Thus, digit identity appears to depend primarily on *Shh* concentration, although it is possible that other signals may relay this information over the substantial distances that appear to be required for AP patterning (100-150μm). Similar to the interaction of HH and DPP in the *Drosophila* imaginal discs, *Shh* in the vertebrate limb bud activates the expression of *Bmp2* (Francis, P.H. *et al.* (1994) Development 120:209-218), a *dpp* homologue. However, unlike DPP in *Drosophila*, BMP2 fails to

mimic the polarizing effect of *Shh* upon ectopic application in the chick limb bud (Francis *et al.* (1994) supra). In addition to anteroposterior patterning, *Shh* also appears to be involved in the regulation of the proximodistal outgrowth of the limbs by inducing the synthesis of the fibroblast growth factor FGF4 in the posterior apical ectodermal ridge (Laufer, E. *et al.* (1994) Cell 79:993-1003; Niswander, L. *et al.*(1994) Nature 371:609-612).

The close relationship between Hedgehog proteins and BMPs is likely to have been conserved at many, but probably not all sites of vertebrate *Hedgehog* expression. For example, in the chick hindgut, *Shh* has been shown to induce the expression of *Bmp4*, another vertebrate *dpp* homologue (Roberts, D.J. *et al.* (1995) Development 121:3163-3174). Furthermore, *Shh* and *Bmp2,4*, or *6* show a striking correlation in their expression in epithelial and mesenchymal cells of the stomach, the urogential system, the lung, the tooth buds and the hair follicles (Bitgood, M.J. and McMahon, A.P. (1995) Dev. Biol. 172:126-138). Further, *Ihh*, one of the two other mouse *Hedgehog* genes, is expressed adjacent to *Bmp* expressing cells in the gut and developing cartilage (Bitgood and McMahon (1995) *supra*).

Recent evidence suggests a model in which *Ihh* plays a crucial role in the regulation of chondrogenic development (Roberts *et al.* (1995) supra). During cartilage formation, chondrocytes proceed from a proliferating state via an intermediate, prehypertrophic state to differentiated hypertrophic chondrocytes. *Ihh* is expressed in the prehypertrophic chondrocytes and initiates a signaling cascade that leads to the blockage of chondrocyte differentiation. Its direct target is the perichondrium around the *Ihh* expression domain, which responds by the expression of *Gli* and *Patched* (*Ptc*), conserved transcriptional targets of Hedgehog signals (see below). Most likely, this leads to secondary signaling resulting in the synthesis of parathyroid hormone-related protein (PTHrP) in the periarticular perichondrium. PTHrP itself signals back to the prehypertrophic chondrocytes, blocking their further differentiation. At the same time, PTHrP represses expression of *Ihh*, thereby forming a negative feedback loop that modulates the rate of chondrocyte differentiation.

Summary of the Invention

The present invention relates to methods and reagents for inhibiting hedgehog signal transduction pathways. For instance, the present invention makes availables methods and reagents for inhibiting paracrine and/or autocrine signals produced by a hedgehog protein comprising contacting a cell sensitive to the hedgehog protein with a steroidal alkaloid, or other small molecule, in a sufficient amount to reduce the sensitivity of the cell to the hedgehog protein. In other aspects, the present invention makes availables methods and reagents for inhibiting abberant growth states resulting from ptc loss-of-function or smoothened gain-of-function comprising contacting the cell with a *ptc* agonist, such as a steroidal alkaloid or other small molecule, in a sufficient amount to abberant growth state, e.g., to agonize a normal ptc pathway or antagonize smoothened activity.

Brief Description of the Drawings

Figure 1. Structures of the synthetic compounds AY 9944 and triparanol, of the plant steriodal alkaloids jervine, cyclopamine and tomatidine, and of cholesterol.

Figure 2. Holoprosencephaly induced in chick embryos exposed to jervine (4). (**A**) SEM of external facial features of an untreated embryo. (**B, C, D** and **E**) Embryos exposed to 10 μ_M jervine with variable loss of midline tissue and resulting fusion of the paired, lateral olfactory processes (olf), optic vesicles (Opt), and maxillary (Mx) and mandibular (Mn) processes. A complete fusion of the optic vesicles (**E**) lead to true cyclopia.

Figure 3. Synthetic and plant derived teratogens block endogenous *Shh* signaling in explanted chick tissues (41). (**A**) Midline tissue was removed from stage 9-10 chick embryos at a level just rostral to Hensen's node (white dashed line), and further dissected (black dashed lines) to yield an explant containing an endogenous source of *Shh* signal (notochord) and a responsive tissue (neural plate ectoderm). After two days of culture in a collagen gel matrix, the neural ectoderm expresses markers of floor plate cells (HNF3β, rhodamine) and motor neurons (Isl-1, FITC) in untreated control explants (**B**) and explants cultured with the non-teratogenic alkaloid tomatidine (50 μM, **C**). Intermedia doses of the teratogenic compounds AY 9944 (0.5 μM, **D**), triparanol (0.25 μM, **E**), jervine (0.5 μM, **F**) and cyclopamine (0.25 μM, **G**) block induction of HNF3β, which requires a high level of *Shh* pathway activation, while permitting induction of Isl-1, which requires a lower level of *Shh* pathway activation (see text). Higher doses of the teratogenic compounds AY 9944 (4.0 μM, **H**), triparanol (1.0 μM, **I**), jervine (4.0 μM, **J**) and cyclopamine (1.0 μM, **K**) and fully inhibit HNF3β and Isl-1 induction.

Figure 4. Teratogenic compounds do not inhibit Shh autoprocessing in vivo (47). Stably transfected HK293 cells expressing Shh protein under ecdysone-inducible control (lanes 1, 2, 3) were treated with jervine (lanes 4, 5) cyclopamine (lanes 6, 7), tomatidine (lanes 10, 11), AY 9944 (lanes 12, 13) or triparanol (lanes 14, 15) and cell lysates were

immunoblotted to assess the efficiency of autoprocessing. As seen in the untreated control (lane 3), Shh in treated cells is efficiently processed with little or no detectable accumulation of precursor protein (M_r45 kD). The processed amino-terminal product (Shh-N_p) is cell associated and migrates faster than Shh-N protein from the media of cultured cells transfected with a construct carrying an open reading frame truncated after Gly_{198} (lane 8; Shh-N_p and Shh-N both loaded in lanes 9 and 17). This faster migration and the lack of detectable protein in the culture medium (not shown) indicate that Shh-N_p from treated cells likely carries a sterol adduct. The slower migrating species resulting from tomatidine treatment is ~ 1.9 kD larger, suggestive of a minor inhibition of signal sequence cleavage (see asterisk; lanes 10, 11). Immunoblotted actin for each lane is shown as a loading control.

Figure 5. Plant steriodal alkaloids do not inhibit or participate in Hh autoprocessing in vitro (5). (A) Coomassie blue-stained SDS-polyacrylamide gel showing in vitro autocleavage reactions of the baterically expressed His_6Hh-C protein (~29 kD) incubated for 3 hours at 30° C with no sterol additions (lane 1) or 12 μM cholesterol to stimulate the autoprocessing reaction and generate a ~25 kD Hh-C product (lanes 2-27 and a ~5 kD NH_2-terminal product (not resolved on this gel). The addition of jervine (lanes 3-6), cyclopamine (lanes 8-11) and tomatidine (lanes 13-16) does not interfere with autoprocessing, even when added in 27-fold excess to cholesterol (lanes 6, 11 and 16). (B) Coomassie blue-stained SDS-polyacrylamide gel showing that the His_6Hh-C autocleavage reaction does not proceed when carried out in the absence of sterol (lane 1), or in the presence of jervine (lanes 2-5), cyclopamine (lanes 6-9) and tomatidine (lanes 10-13), even at 324 μM concentrations of these steriodal alkaloid (lanes 5, 9 and 13). (C) Coomassie blue-stained SDS0 polyacrylamide gel of His_6Hh-C autocleavage reactions carried out in the absence of sterols (lane 1), with 50 mM dithiothreitol (lane 2), 12 μM cholesterol (lane 3) 12 μM7 dehydrocholesterol (lane 4) 12 μM desmosterol (lane 5), 12 μM muristerone (lanes 9, 10). The 27-carbon cholesterol precursors (lanes 4-6) stimulate His_6Hh-C autocleavage reactions carried out in the absence of sterols (lane 1), with 50 mM dithiothreitol (lane 2), 12 μM cholesterol (lane 3) 12 μM 7 dehydrocholesterol (lane 4) 12 μM lathosterol (lane 6), 12 and 350 μM lanosterol (lanes 7, 8) and 12 and 350 μM muristerone (lanes 9, 10). The 27-carbon cholesterol precursors (lanes 4-6) stimulate His_6Hh-C autoprocessing as efficiently as cholesterol (lane 3). The amino-terminal product migrates as a ~7 kD species (lane 2) when generated in the presence of 50 mM dithiothreitol and as a ~5 kD species (lanes 3-6) with a sterol adduct. Lanosterol (lanes 7 and 8) and muristerone (lanes 9 and 10) do not stimulate autoprocessing above background (lane 1).

Figure 6. Teratogenic compounds inhibit neural ectoderm response to exogenous Shh-N protein (41). (A) Intermediate neural plate ectoderm, free of notochord and other tissues, was dissected as shown (dashed lines) from stage 9-10 chick embryos at a level just rostral to Hensen's node (see figure 3A). (B) Explanted intermediate neural plate tissue cultured in a collagen gel matrix for 20 hours expresses the dorsal marker Pax7 (FITC) and not the floor plate marker HNF3β (Rhodamine). (C) Addition of recombinant, purified Shh-N at 2 nM suppresses Pax7 expression. (D) Markers of motor neuron (Isl-1, FITC) and floor plate cell (HNF3β, rhodamine) fates are induced upon explant culture for 40 hours in the presence of 6.25 nM Shh-N. (E) At 25 nM Shh-N, HNF3β expression expands at the expense of Isl-1 expression, which is lost. The repression of Pax7 expression by 2 nM Shh-N is inhibited by (F) 0.5 μM AY 9944, (G) 0.25 μM triparanol, (H) 0.125 μM jervine and (I) 0.0625 μM cyclopamine, but not by (J) 50 μM tomatidine. Induction of HNF3β is blocked while induction of Isl-1 at 25 NM Shh-N is maintained or expanded at intermediate levels of AY 9949 (1.0 μM, K), triparanol (0.25 μM, L), jervine (0.25 μM, M), and cyclopamine (0.125 μM, N). Tomatidine at 25 nM displays a slight inhibitory effect with decrease in HNF3β expression and an increase in the number Isl-1 expressing cells. HNF3β and Is1-1 induction are completely blocked at 2-fold higher doses of inhibitors AY 9944 (2.0 μM, P), triparanol (0.5 μM, Q), jervine (0.5, μM, R) and cyclopamine (0.25 μM, S). Tomatidine at 50 μM (T) markedly reduces HNF3β induction and enhances Isl1-1 induction. Note that for each teratogenic compound the concentrations required to block complete the response to 2nM Shh-N (F-I) are lower than those required to block completely the response to 25 nM Shh-N (P-S). Also note that the response to 25 nM Shh-N is only partially inhibited (K-N) at concentrations of teratogen 2 fold lower than those required to block this response completely. See text for further comment.

Figure 7. Jervine does not inhibit neural ectoderm response to BMP7 (41). (A) Ventral neural plate ectoderm was dissected as shown (dashed lines) from stage 9-10 chick embryos at a level just rostral to Hensen's node (see Fig. 3A). (B) Ventral neural plate explants cultured for 24 hours in a collagen gel matrix do not give rise to any migratory cells that can be visualized by immunostaining for the HNK-1 antigen. (C) Addition of 100 ng/ml BMP7 induces formation of numerous HNK-1 positive cells that migrate out from the explant (borders outlined by white dashed line). (D) Induction of migratory HNK-1 positive cells by 100 ng/ml BMP7 is not inhibited by the presence of 10 μM jervine, nor by addition of the other plant-derived compounds (10 μM cyclopamine, 50. μM tomatidine; data not shown).

Figure 8. Morphology and gene expression patterns of control and *Shh* -/- primary hair germs. (A,B) Normal-appearing hair genus consisting of an epithelial placode and adjacent mesenchymal condensate (arrows) were detected in skin of both control (A) and *Shh -/- (B)* embryos at 15.5 days of gestation (H&E staining). (C-H) Altered abundance of Shh target genes in hair germs in *Shh* -/- mouse skin. Expression of Glil (C,D), Ptcl. (E,F), and *BMP-4* (G,H) transcripts was examined in E 15.5 mouse skin using digoxigenin-labeled cRNA probes. Note virtual absence of Glil in both epithelial and mesenchymal components of the mutant hair germ and reduced mesenchymal Ptcl expression in *Shh* -/- skin.

Figure 9. Inhibition of hair follicle morphogenesis, but not biochemical differentiation, in *Shh* -/- mouse skin. (A,B) Advanced hair follicle development in skin from control (A) but not *Shh* -/- (B) embryos at 17.5 days of gestation (H&E staining). Note dermal papilla (arrow) surrounded by epithelial bulb of the largest hair follicle, and organizing mesenchymal aggregates (arrowheads) adjacent to invaginating tips of less mature follicles (A). In striking contrast, dermal papillae are not detected in Shh mutant skin (B). (C-F) Immunohistochemistry revealing similar patterns of keratin expression in control and Shh-deficient follicles. Absence of keratin K 14 immunostaining in subpopulation of keratinocytes in both control (C) and *Shh* -/- (D) hair follicles (arrows). Induction of non-epidermal. keratin K17 in hair follicle keratinocytes in control (E) and *Shh* mutant (F) skin.

Figure 10. Impaired hair follicle development in *Shh* mutant skin grafted onto nude mice. (A) Gross appearance of nude mouse graft sites 6 weeks after transplantation. Note robust hair growth in control graft compared to hairless, but pigmented, *Shh* -/- skin graft. (B,C) H&E staining. Histologically normal-appearing skin in control graft (B) contains mature hair follicles with associated sebaceous glands and subcutaneous adipose tissue. Abnormal skin development in *Shh* -/- graft characterized by a thickened epidermis containing keratinocyte aggregates (arrows) at the base of the epidermis (C). (D-F) Immunchistochemistry. Unlike adjacent epidermal cells, *Shh* -/- keratinocyte aggregates do not express K5 (D, arrows) but are positive for Lef-l localized to nuclei (E). Note also the presence of a small cluster of Lef-1 positive mesenchymal cells associated with the keratinocyte aggregate on the right (E). Immunostaining of abortive hair shafts with hair-specific keratin antibody AE 13 (F), revealing an advanced stage of follicle differentiation in *Shh* mutant skin.

Figure 11. Cyclopamine impairs vibrissa follicle morphogenesis in explant cultures. (A) vibrissa pad explants growing on Nuclepore membranes on day one and day eight in culture (dark-field). (B) FC-PCR analysis examining expression of transcripts

encoding hair-specific markers MHKAI and Hacl-1, and an epidermal differentiation marker filaggrin (profio. RNA was obtained from embryonic vibrissa pads when first isolated (Day 0) and after growth as explants (Day 7) in the presence or absence of I ~M cyclopamine. Each lane contains reaction products for RNA isolated from an individual vibrissa pad. C) Morphogenesis of vibrissa follicles is blocked by cyclopamine, an inhibitor of Shh signaling. Cyclopamine was present in the medium for the duration of the experiment.

Figure 12. Ptc +/- MEFs incubated with *Shh*Np for 5 days.

Figure 13. Ptc -/- MEFs 23-1 cultured with cyclopamine for 3 days.

Figure 14. Ptc -/- MEFs 23-4 cultured with cyclopamine for 16 hours.

Figure 15. Ptc -/- MEFs 21-4 cultured with tomatidine for 16 hours.

Detailed Description of the Invention

Hedgehog (*hedgehog*) proteins comprise a family of secreted signaling molecules essential for patterning a variety of structures in animal embryo genesis, and play a role in regulating cell proliferation and specifying cell identity in diverse systems in adults.

During biosynthesis, *hedgehog* undergoes an autocleavage reaction, mediated by its carboxyl-terminal domain, that produces a lipid-modified amino-terminal fragment responsible for all known *hedgehog* signaling activity. In addition to peptide bond cleavage, *hedgehog* autoprocessing causes the covalent attachment of a lipophilic adduct to the COOH-terminus of N-terminal *hedgehog* fragment. This modification is critical for the spatially restricted tissue localization of the *hedgehog* signal; in its absence, the signaling domain exerts an inappropriate influence beyond its site of expression. It has recently been reported, Porter et al. (1996) Science 274:255, that cholesterol is the lipophilic moiety covalently attached to the amino-terminal signaling domain during autoprocessing and that the carboxyl-terminal domain acts as an intramolecular cholesterol transferase. This use of cholesterol to modify the *hedgehog* signaling proteins is consistent with some of the effects that perturbed cholesterol biosynthesis can have on animal development. See also Volhard et al. (1998) Nature 287 795; Mohleret al. (1988) Genetics 120:1061; Lee et al. (1992) Cell 71:33; Tabata et al. (1992) Genes Dev 6:2635; Tashiro et al (1993) Genel 24:183; P. W. Ingham, Nature 366:560 (1993); Mohler et al. Development 115:957 (1992); Ma et al. Cell 75:927 (1993); Heberlein et al. ibid, p.913;. Echelard et al., Ibid, p. 1417; Riddle et al. ibid., p. 1401; Krauss et al. , ibid., p. 1431; Roelink et al., ibid 76, 761 (1994); Chang et al., Development 120:3339 (1994); Basler et al. Nature 368:208

(1994); Tabata et al. Cell 76:89 (1994); Heemskerk et al., ibid., p. 449; Fan et al., ibid. 79:1175 (1994); Johnson et al., ibid., p. 1165; Hynes et al., Neuron 15:35 (1995); Ekker et al., Development 121:2337 (1995); Macdonald et al., ibid, p. 3267; Ekker et al., Curr. Biol 5:944 (1995); Lai et al. Development 121, 2349 (1995); Ericson et al., Cell 81:747 (1995). Chiang et al., Nature 83:407 (1996); Bitgood et al. Curr Biol. 6:298 (1996); Vortkamp et al., Science 273:613 (1996); Lee et al., ibid. 266:1528 (1994); Porter et al., Nature 374: 363 (1995); Porter et al. Cell 86:21 (1996).

I. Overview

The present invention relates to the discovery that signal transduction pathways induced by hedgehog proteins can be inhibited, at least in part, by compounds which disrupt the cholesterol modification of hedgehog proteins and/or which inhibit the bioactivity of hedgehog proteins. In particular, Applicants believe that they are the first to demonstrate that a small molecule, e.g., having a molecular weight less than 2500 amu, is capable of inhibiting at least some of the biological activities induced by the hedgehog signal transduction pathway. For example, the subject inhibitors can be used to inhibit hedgegog-dependent signal transductions, as well as *ptc*^{lof}- and *smo*^{gof}-mediated signaling.

One aspect of the present invention relates to the use of steroidal alkaloids, and analogs thereof, to interfere with paracrine and/or autocrine signals produced by the hedgehog proteins, particularly cholesterol-modified (CM) forms of the proteins, as well constitutive signaling caused by loss-of-function mutation of ptc or gain-of-function mutations of smo. As set out in more detail below, we have observed that members of the steroidal alkaloid class of compounds, such as the *Veratrum*-derived compound jervine, disrupt such signals and the concomitant biological response of the cell.

While not wishing to bound by any particular theory, the ability of jervine and other steroidal alkaloids to inhibit hedgehog signaling may be due to the ability of such molecules to interact with the patched or smoothened, or at least interfere with the ability of those proteins to activate a ptc and/or smoothened-mediated signal transduction pathway. For instance the subject inhibitors may interact with the sterol sensing domain(s) of the hedgehog receptor, patched, or at least to interfere with the ability of a hedgehog protein, e.g., a cholesterol-modified protein, to interact with its receptor, or other molecules associated with the receptor, or proteins otherwise involved in hedgehog-mediated signal transduction.

Alternatively, or in addition to such a mechanism of action, the effects of jervine on hedgehog signaling could be the result of perturbations of cholesterol homeostasis

which affect cholesterol-mediated autoprocessing of the hedgehog protein and or the activity or stability of protein. In particular, as described in the appended examples, Jervine and other of the steroidal alkaloids are so-called "class 2" inhibitors of cholesterol biosynthesis, that is they inhibit the inward flux of sterols. As described by Lange and Steck (1994) J Biol Chem 269: 29371-4, these inhibitors immediately inhibit plasma membrane cholesterol esterification and progressively induce 3-hydroxy-3-methylglutaryl-coenzyme A reductase activity and sterol biosynthesis. The change in the relative cholesterol levels can effect, e.g., the activity and/or stability of ptc. According to the present invention, the subject methods may be carried out utilizing other agents which perturb cholesterol homeostasis in a manner similar to jervine.

It is, therefore, specifically contemplated that other small molecules, steroidal and non-steroidal in structure, which similarly interfere with cholesterol dependent aspects of ptc activity will likewise be capable of disrupting hedgehog-mediated signals. In preferred embodiments, the subject inhibitors are organic molecules having a molecular weight less than 2500 amu, more preferably less than 1500 amu, and even more preferably less than 750 amu, and are capable of inhibiting at least some of the biological activities of hedgehog proteins.

Thus, the methods of the present include the use of steroidal alkaloids, and other small molecules, which antagonize *hedgehog* signal pathways, e.g. such as by inhibiting activations of smoothened or downstream components of the signal pathway, in the regulation of repair and/or functional performance of a wide range of cells, tissues and organs, and have therapeutic and cosmetic applications ranging from regulation of neural tissues, bone and cartilage formation and repair, regulation of spermatogenesis, regulation of smooth muscle, regulation of lung, liver and other organs arising from the primative gut, regulation of hematopoietic function, regulation of skin and hair growth, etc. Accordingly, the methods and compositions of the present invention include the use of the subject inhibitors for all such uses as antagonists of hedgehog proteins may be implicated. Moreover, the subject methods can be performed on cells which are provided in culture (*in vitro*), or on cells in a whole animal (*in vivo*). See, for example, PCT publications WO 95/18856 and WO 96/17924 (the specifications of which are expressly incorporated by reference herein).

In a preferred embodiment, the subject method can be to treat epithelial cells having a phenotype of hedgehog gain-of-function, *ptc* loss-of-function or smoothened gain-of-function. For instance the subject method can be used in treating or preventing basal cell carcinoma or other proliferative disorders.

In one aspect, the present invention provides pharmaceutical preparations comprising, as an active ingredient, an inhibitor of *hedgehog* signal pathways, such as described herein.

The subject treatments using the inhibitors of the present inventions can be effective for both human and animal subjects. Animal subjects to which the invention is applicable extend to both domestic animals and livestock, raised either as pets or for commercial purposes. Examples are dogs, cats, cattle, horses, sheep, hogs and goats.

II. Definitions

For convenience, certain terms employed in the specification, examples, and appended claims are collected here.

The term "hedgehog polypeptide" encompasses preparations of *hedgehog* proteins and peptidyl fragments thereof, both agonist and antagonist forms as the specific context will make clear.

The term "hedgehog gain-of-function" refers to a mutation of hedgehog coding sequence which gives rise to a form of the protein which is more active, with respect to ptc-dependent activities, than the wild-type protein. Hedgehog gain-of-function can also include aberrant expressions of the wild-type protein, e.g. where the protein is expressed at abnormally high levels, or has an increased half-life, or is incorrectly modified (by post-translational processes), or is expressed at the wrong time (ectopic expression).

The term "*ptc* loss-of-function" refers to an aberrant modification or mutation of a *ptc* gene, or a decrease (or loss) in the level of expression of the gene, which results in a phenotype which resembles contacting the cell with a hedgehog protein, e.g., aberrant activation of a hedgehog pathway. The loss-of-function may include a loss of the ability of the *ptc* gene product to regulate the level of expression of Ci genes, e.g., Gli1, Gli2 and Gli3.

The term "smoothened gain-of-function" refers to an aberrant modification or mutation of a *ptc* gene, or an increased level of expression of the gene, which results in a phenotype which resembles contacting the cell with a hedgehog protein, e.g., aberrant activation of a hedgehog pathway. While not wishing to be bound by any particular theory, it is noted that *ptc* may not signal directly into the cell, but rather interact with smoothened, another membrane-bound protein located downstream of *ptc* in hedgehog signaling (Marigo et al., (1996) Nature 384: 177-179). The gene *smo* is a segment-polarity gene required for the correct patterning of every segment in Drosophila (Alcedo et al.,

(1996) Cell 86: 221-232). Human homologs of *smo* have been identified. See, for example, Stone et al. (1996) Nature 384:129-134, and GenBank accession U84401. The smoothened gene encodes an integral membrane protein with characteristics of heterotrimeric G protein-coupled receptors; i.e., 7- transmembrane regions. This protein shows homology to the Drosophila Frizzled (Fz) protein, a member of the wingless pathway. It was originally thought that *smo* encodes a receptor of the Hh signal. However, this suggestion was subsequently disproved as evidence for *Ptc* being the Hh receptor was obtained. Cells that express *Smo* fail to bind Hh, indicating that *Smo* does not interact directly with Hh (Nusse, (1996) Nature 384: 119-120). Rather, the binding of Sonic hedgehog (SHH) to its receptor, *PTCH*, is thought to prevent normal inhibition by *PTCH* of Smoothened (SMO), a seven-span transmembrane protein.

Recently, it has been reported that activating Smoothened mutations occur in sporadic basal cell carcinoma, Xie et al. (1998) Nature 391: 90-2, and primitive neuroectodermal tumors of the central nervous system, Reifenberger et al. (1998) Cancer Res 58: 1798-803.

The phrase "aberrant modification or mutation" of a gene refers to such genetic lesions as, for example, deletions, substitution or addition of nucleotides to a gene, as well as gross chromosomal rearrangements of the gene and/or abnormal methylation of the gene. Likewise, mis-expression of a gene refers to aberrant levels of transcription of the gene relative to those levels in a normal cell under similar conditions, as well as non-wild type splicing of mRNA transcribed from the gene.

The term "hedgehog antagonist", refers to a compound that a hedgehog signaling pathway. Thus, the term includes inhibitors of hedgehog-mediated signal transductions, as well as hedgehog-independent signal such as resulting from *ptc*^{lof} or *smo*^{gof} mutations. In the context of the present invention, such antagonists can include compounds which mimic the activity of jervine, having such characteristics as the ability to disrupt cholesterol homoeostasis such as through inhibition of sterol trafficking (e.g., a class 2 inhibitor), the ability to bind to a hedgehog receptor site and inhibit the simultaneous binding of hedgehog to the receptor, or, by non-competitive and/or allosteric effects of the like, inhibit the response of the cell to hedgehog which does bind, or inhibits the effect of *ptc*^{lof} or *smo*^{gof}, e.g. reverses the phenotype to resemble the wild-type phenotype. Thus, the term includes *ptc* agonists and smoothened antagonists.

The term "*ptc* agonist" refers to an agent which potentiates or recapitulates the bioactivity of *ptc*, such as to repression transcription of target genes. Preferred *ptc* agonists can be used to overcome a *ptc* loss-of-function and/or a *smoothened* gain-of-function, the latter also being referred to as smoothened antagonists.

The term "competitive antagonist" refers to a compound that binds to a receptor site; its effects can be overcome by increased concentration of the agonist.

An "effective amount" of, e.g., a hedgehog antagonist, with respect to the subject method of treatment, refers to an amount of the antagonist in a preparation which, when applied as part of a desired dosage regimen brings about, e.g., a change in the rate of cell proliferation and/or the state of differentiation of a cell and/or rate of survival of a cell according to clinically acceptable standards for the disorder to be treated or the cosmetic purpose.

A "patient" or "subject" to be treated by the subject method can mean either a human or non-human animal.

The "growth state" of a cell refers to the rate of proliferation of the cell and/or the state of differentiation of the cell.

The terms "steroid" and "steroid-like" are used interchangeable herein and refer to a general class of polycyclic compounds possessing the skeleton of cyclopentanophenanthrene or a skeleton derived therefrom by one or more bond scissions or ring expansions or contractions. The rings may be substituted at one or more positions, to create derivatives that adhere to the rules of valence and stability, such as by methyl or other lower alkyl groups, hydroxyl groups, alkoxyl groups and the like.

The terms "epithelia", "epithelial" and "epithelium" refer to the cellular covering of internal and external body surfaces (cutaneous, mucous and serous), including the glands and other structures derived therefrom, e.g., corneal, esophageal, epidermal, and hair follicle epithelial cells. Other exemplary epithelial tissue includes: olfactory epithelium, which is the pseudostratified epithelium lining the olfactory region of the nasal cavity, and containing the receptors for the sense of smell; glandular epithelium, which refers to epithelium composed of secreting cells; squamous epithelium, which refers to epithelium composed of flattened plate-like cells. The term epithelium can also refer to transitional epithelium, like that which is characteristically found lining hollow organs that are subject to great mechanical change due to contraction and distention, e.g. tissue which represents a transition between stratified squamous and columnar epithelium.

The term "epithelialization" refers to healing by the growth of epithelial tissue over a denuded surface.

The term "skin" refers to the outer protective covering of the body, consisting of the corium and the epidermis, and is understood to include sweat and sebaceous glands, as well as hair follicle structures. Throughout the present application, the adjective

"cutaneous" may be used, and should be understood to refer generally to attributes of the skin, as appropriate to the context in which they are used.

The term "epidermis" refers to the outermost and nonvascular layer of the skin, derived from the embryonic ectoderm, varying in thickness from 0.07-1.4 mm. On the palmar and plantar surfaces it comprises, from within outward, five layers: basal layer composed of columnar cells arranged perpendicularly; prickle-cell or spinous layer composed of flattened polyhedral cells with short processes or spines; granular layer composed of flattened granular cells; clear layer composed of several layers of clear, transparent cells in which the nuclei are indistinct or absent; and horny layer composed of flattened, cornified non-nucleated cells. In the epidermis of the general body surface, the clear layer is usually absent.

The "corium" or "dermis" refers to the layer of the skin deep to the epidermis, consisting of a dense bed of vascular connective tissue, and containing the nerves and terminal organs of sensation. The hair roots, and sebaceous and sweat glands are structures of the epidermis which are deeply embedded in the dermis.

The term "nail" refers to the horny cutaneous plate on the dorsal surface of the distal end of a finger or toe.

The term "epidermal gland" refers to an aggregation of cells associated with the epidermis and specialized to secrete or excrete materials not related to their ordinary metabolic needs. For example, "sebaceous glands" are holocrine glands in the corium that secrete an oily substance and sebum. The term "sweat glands" refers to glands that secrete sweat, situated in the corium or subcutaneous tissue, opening by a duct on the body surface.

The term "hair" refers to a threadlike structure, especially the specialized epidermal structure composed of keratin and developing from a papilla sunk in the corium, produced only by mammals and characteristic of that group of animals. Also, the aggregate of such hairs. A "hair follicle" refers to one of the tubular-invaginations of the epidermis enclosing the hairs, and from which the hairs grow; and "hair follicle epithelial cells" refers to epithelial cells which surround the dermal papilla in the hair follicle, e.g., stem cells, outer root sheath cells, matrix cells, and inner root sheath cells. Such cells may be normal non-malignant cells, or transformed/immortalized cells.

The term "nasal epithelial tissue" refers to nasal and olfactory epithelium.

"Excisional wounds" include tears, abrasions, cuts, punctures or lacerations in the epithelial layer of the skin and may extend into the dermal layer and even into

subcutaneous fat and beyond. Excisional wounds can result from surgical procedures or from accidental penetration of the skin.

"Burn wounds" refer to cases where large surface areas of skin have been removed or lost from an individual due to heat and/or chemical agents.

"Dermal skin ulcers" refer to lesions on the skin caused by superficial loss of tissue, usually with inflammation. Dermal skin ulcers which can be treated by the method of the present invention include decubitus ulcers, diabetic ulcers, venous stasis ulcers and arterial ulcers. Decubitus wounds refer to chronic ulcers that result from pressure applied to areas of the skin for extended periods of time. Wounds of this type are often called bedsores or pressure sores. Venous stasis ulcers result from the stagnation of blood or other fluids from defective veins. Arterial ulcers refer to necrotic skin in the area around arteries having poor blood flow.

"Dental tissue" refers to tissue in the mouth which is similar to epithelial tissue, for example gum tissue. The method of the present invention is useful for treating periodontal disease.

"Internal epithelial tissue" refers to tissue inside the body which has characteristics similar to the epidermal layer in the skin. Examples include the lining of the intestine. The method of the present invention is useful for promoting the healing of certain internal wounds, for example wounds resulting from surgery.

A "wound to eye tissue" refers to severe dry eye syndrome, corneal ulcers and abrasions and ophthalmic surgical wounds.

Throughout this application, the term "proliferative skin disorder" refers to any disease/disorder of the skin marked by unwanted or aberrant proliferation of cutaneous tissue. These conditions are typically characterized by epidermal cell proliferation or incomplete cell differentiation, and include, for example, X-linked ichthyosis, psoriasis, atopic dermatitis, allergic contact dermatitis, epidermolytic hyperkeratosis, and seborrheic dermatitis. For example, epidermodysplasia is a form of faulty development of the epidermis.. Another example is "epidermolysis", which refers to a loosened state of the epidermis with formation of blebs and bullae either spontaneously or at the site of trauma.

The term "carcinoma" refers to a malignant new growth made up of epithelial cells tending to infiltrate surrounding tissues and to give rise to metastases. Exemplary carcinomas include: "basal cell carcinoma", which is an epithelial tumor of the skin that, while seldom metastasizing, has potentialities for local invasion and destruction; "squamous cell carcinoma", which refers to carcinomas arising from squamous epithelium and having cuboid cells; "carcinosarcoma", which include malignant tumors composed of

carcinomatous and sarcomatous tissues; "adenocystic carcinoma", carcinoma marked by cylinders or bands of hyaline or mucinous stroma separated or surrounded by nests or cords of small epithelial cells, occurring in the mammary and salivary glands, and mucous glands of the respiratory tract; "epidermoid carcinoma", which refers to cancerous cells which tend to differentiate in the same way as those of the epidermis; i.e., they tend to form prickle cells and undergo cornification; "nasopharyngeal carcinoma", which refers to a malignant tumor arising in the epithelial lining of the space behind the nose; and "renal cell carcinoma", which pertains to carcinoma of the renal parenchyma composed of tubular cells in varying arrangements. Another carcinomatous epithelial growth is "papillomas", which refers to benign tumors derived from epithelium and having a papillomavirus as a causative agent; and "epidermoidomas", which refers to a cerebral or meningeal tumor formed by inclusion of ectodermal elements at the time of closure of the neural groove.

"Basal cell carcinomas" exist in a variety of clinical and histological forms such as nodular-ulcerative, superficial, pigmented, morphealike, fibroepithelioma and nevoid syndrome. Basal cell carcinomas are the most common cutaneous neoplasms found in humans. The majority of the 500,000 new cases of nonmelanoma skin cancers each

As used herein, the term "psoriasis" refers to a hyperproliferative skin disorder which alters the skin's regulatory mechanisms. In particular, lesions are formed which involve primary and secondary alterations in epidermal proliferation, inflammatory responses of the skin, and an expression of regulatory molecules such as lymphokines and inflammatory factors. Psoriatic skin is morphologically characterized by an increased turnover of epidermal cells, thickened epidermis, abnormal keratinization, inflammatory cell infiltrates into the dermis layer and polymorphonuclear leukocyte infiltration into the epidermis layer resulting in an increase in the basal cell cycle. Additionally, hyperkeratotic and parakeratotic cells are present.

The term "keratosis" refers to proliferative skin disorder characterized by hyperplasia of the horny layer of the epidermis. Exemplary keratotic disorders include keratosis follicularis, keratosis palmaris et plantaris, keratosis pharyngea, keratosis pilaris, and actinic keratosis.

As used herein, "proliferating" and "proliferation" refer to cells undergoing mitosis.

As used herein, "transformed cells" refers to cells which have spontaneously converted to a state of unrestrained growth, i.e., they have acquired the ability to grow through an indefinite number of divisions in culture. Transformed cells may be characterized by such terms as neoplastic, anaplastic and/or hyperplastic, with respect to their loss of growth control.

As used herein, "immortalized cells" refers to cells which have been altered via chemical and/or recombinant means such that the cells have the ability to grow through an indefinite number of divisions in culture.

The term "prodrug" is intended to encompass compounds which, under physiological conditions, are converted into the therapeutically active agents of the present invention. A common method for making a prodrug is to select moieties which are hydrolyzed under physiological conditions to provide the desired. In other embodiments, the prodrug is converted by an enzymatic activity of the host animal.

The term "heteroatom" as used herein means an atom of any element other than carbon or hydrogen. Preferred heteroatoms are boron, nitrogen, oxygen, phosphorus, sulfur and selenium.

Herein, the term "aliphatic group" refers to a straight-chain, branched-chain, or cyclic aliphatic hydrocarbon group and includes saturated and unsaturated aliphatic groups, such as an alkyl group, an alkenyl group, and an alkynyl group.

The term "alkyl" refers to the radical of saturated aliphatic groups, including straight-chain alkyl groups, branched-chain alkyl groups, cycloalkyl (alicyclic) groups, alkyl substituted cycloalkyl groups, and cycloalkyl substituted alkyl groups. In preferred embodiments, a straight chain or branched chain alkyl has 30 or fewer carbon atoms in its backbone (e.g., C_1-C_{30} for straight chain, C_3-C_{30} for branched chain), and more preferably 20 or fewer. Likewise, preferred cycloalkyls have from 3-10 carbon atoms in their ring structure, and more preferably have 5, 6 or 7 carbons in the ring structure.

Moreover, the term "alkyl" (or "lower alkyl") as used throughout the specification, examples, and claims is intended to include both "unsubstituted alkyls" and "substituted alkyls", the latter of which refers to alkyl moieties having substituents replacing a hydrogen on one or more carbons of the hydrocarbon backbone. Such substituents can include, for example, a halogen, a hydroxyl, a carbonyl (such as a carboxyl, an alkoxycarbonyl, a formyl, or an acyl), a thiocarbonyl (such as a thioester, a thioacetate, or a thioformate), an alkoxyl, a phosphoryl, a phosphonate, a phosphinate, an amino, an amido, an amidine, an imine, a cyano, a nitro, an azido, a sulfhydryl, an alkylthio, a sulfate, a sulfonate, a sulfamoyl, a sulfonamido, a sulfonyl, a heterocyclyl, an aralkyl, or an aromatic or heteroaromatic moiety. It will be understood by those skilled in the art that the moieties substituted on the hydrocarbon chain can themselves be substituted, if appropriate. For instance, the substituents of a substituted alkyl may include substituted and unsubstituted forms of amino, azido, imino, amido, phosphoryl (including phosphonate and phosphinate), sulfonyl (including sulfate, sulfonamido, sulfamoyl and

sulfonate), and silyl groups, as well as ethers, alkylthios, carbonyls (including ketones, aldehydes, carboxylates, and esters), -CF_3, -CN and the like. Exemplary substituted alkyls are described below. Cycloalkyls can be further substituted with alkyls, alkenyls, alkoxys, alkylthios, aminoalkyls, carbonyl-substituted alkyls, -CF_3, -CN, and the like.

The term "aralkyl", as used herein, refers to an alkyl group substituted with an aryl group (e.g., an aromatic or heteroaromatic group).

The terms "alkenyl" and "alkynyl" refer to unsaturated aliphatic groups analogous in length and possible substitution to the alkyls described above, but that contain at least one double or triple bond respectively.

Unless the number of carbons is otherwise specified, "lower alkyl" as used herein means an alkyl group, as defined above, but having from one to ten carbons, more preferably from one to six carbon atoms in its backbone structure. Likewise, "lower alkenyl" and "lower alkynyl" have similar chain lengths. Throughout the application, preferred alkyl groups are lower alkyls. In preferred embodiments, a substituent designated herein as alkyl is a lower alkyl.

The term "aryl" as used herein includes 5-, 6- and 7-membered single-ring aromatic groups that may include from zero to four heteroatoms, for example, benzene, pyrrole, furan, thiophene, imidazole, oxazole, thiazole, triazole, pyrazole, pyridine, pyrazine, pyridazine and pyrimidine, and the like. Those aryl groups having heteroatoms in the ring structure may also be referred to as "aryl heterocycles" or "heteroaromatics." The aromatic ring can be substituted at one or more ring positions with such substituents as described above, for example, halogen, azide, alkyl, aralkyl, alkenyl, alkynyl, cycloalkyl, hydroxyl, alkoxyl, amino, nitro, sulfhydryl, imino, amido, phosphonate, phosphinate, carbonyl, carboxyl, silyl, ether, alkylthio, sulfonyl, sulfonamido, ketone, aldehyde, ester, heterocyclyl, aromatic or heteroaromatic moieties, -CF_3, -CN, or the like. The term "aryl" also includes polycyclic ring systems having two or more cyclic rings in which two or more carbons are common to two adjoining rings (the rings are "fused rings") wherein at least one of the rings is aromatic, e.g., the other cyclic rings can be cycloalkyls, cycloalkenyls, cycloalkynyls, aryls and/or heterocyclyls.

The abbreviations Me, Et, Ph, Tf, Nf, Ts, Ms represent methyl, ethyl, phenyl, trifluoromethanesulfonyl, nonafluorobutanesulfonyl, *p*-toluenesulfonyl and methanesulfonyl, respectively. A more comprehensive list of the abbreviations utilized by organic chemists of ordinary skill in the art appears in the first issue of each volume of the *Journal of Organic Chemistry*; this list is typically presented in a table entitled Standard List of Abbreviations. The abbreviations contained in said list, and all abbreviations

utilized by organic chemists of ordinary skill in the art are hereby incorporated by reference.

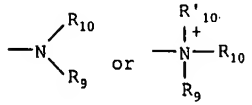
The terms "heterocyclyl" or "heterocyclic group" refer to 3- to 10-membered ring structures, more preferably 3- to 7-membered rings, whose ring structures include one to four heteroatoms. Heterocycles can also be polycycles. Heterocyclyl groups include, for example, thiophene, thianthrene, furan, pyran, isobenzofuran, chromene, xanthene, phenoxathiin, pyrrole, imidazole, pyrazole, isothiazole, isoxazole, pyridine, pyrazine, pyrimidine, pyridazine, indolizine, isoindole, indole, indazole, purine, quinolizine, isoquinoline, quinoline, phthalazine, naphthyridine, quinoxaline, quinazoline, cinnoline, pteridine, carbazole, carboline, phenanthridine, acridine, pyrimidine, phenanthroline, phenazine, phenarsazine, phenothiazine, furazan, phenoxazine, pyrrolidine, oxolane, thiolane, oxazole, piperidine, piperazine, morpholine, lactones, lactams such as azetidinones and pyrrolidinones, sultams, sultones, and the like. The heterocyclic ring can be substituted at one or more positions with such substituents as described above, as for example, halogen, alkyl, aralkyl, alkenyl, alkynyl, cycloalkyl, hydroxyl, amino, nitro, sulfhydryl, imino, amido, phosphonate, phosphinate, carbonyl, carboxyl, silyl, ether, alkylthio, sulfonyl, ketone, aldehyde, ester, a heterocyclyl, an aromatic or heteroaromatic moiety, $-CF_3$, -CN, or the like.

The terms "polycyclyl" or "polycyclic group" refer to two or more rings (e.g., cycloalkyls, cycloalkenyls, cycloalkynyls, aryls and/or heterocyclyls) in which two or more carbons are common to two adjoining rings, e.g., the rings are "fused rings". Rings that are joined through non-adjacent atoms are termed "bridged" rings. Each of the rings of the polycycle can be substituted with such substituents as described above, as for example, halogen, alkyl, aralkyl, alkenyl, alkynyl, cycloalkyl, hydroxyl, amino, nitro, sulfhydryl, imino, amido, phosphonate, phosphinate, carbonyl, carboxyl, silyl, ether, alkylthio, sulfonyl, ketone, aldehyde, ester, a heterocyclyl, an aromatic or heteroaromatic moiety, $-CF_3$, -CN, or the like.

The term "carbocycle", as used herein, refers to an aromatic or non-aromatic ring in which each atom of the ring is carbon.

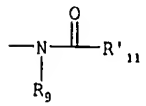
As used herein, the term "nitro" means $-NO_2$; the term "halogen" designates -F, -Cl, -Br or -I; the term "sulfhydryl" means -SH; the term "hydroxyl" means -OH; and the term "sulfonyl" means $-SO_2-$.

The terms "amine" and "amino" are art-recognized and refer to both unsubstituted and substituted amines, e.g., a moiety that can be represented by the general formula:



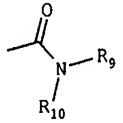
wherein R_9, R_{10} and R'_{10} each independently represent a hydrogen, an alkyl, an alkenyl, $-(CH_2)_m-R_8$, or R_9 and R_{10} taken together with the N atom to which they are attached complete a heterocycle having from 4 to 8 atoms in the ring structure; R_8 represents an aryl, a cycloalkyl, a cycloalkenyl, a heterocycle or a polycycle; and m is zero or an integer in the range of 1 to 8. In preferred embodiments, only one of R_9 or R_{10} can be a carbonyl, e.g., R_9, R_{10} and the nitrogen together do not form an imide. In even more preferred embodiments, R_9 and R_{10} (and optionally R'_{10}) each independently represent a hydrogen, an alkyl, an alkenyl, or $-(CH_2)_m-R_8$. Thus, the term "alkylamine" as used herein means an amine group, as defined above, having a substituted or unsubstituted alkyl attached thereto, i.e., at least one of R_9 and R_{10} is an alkyl group.

The term "acylamino" is art-recognized and refers to a moiety that can be represented by the general formula:



wherein R_9 is as defined above, and R'_{11} represents a hydrogen, an alkyl, an alkenyl or $-(CH_2)_m-R_8$, where m and R_8 are as defined above.

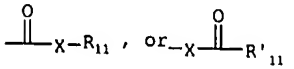
The term "amido" is art recognized as an amino-substituted carbonyl and includes a moiety that can be represented by the general formula:



wherein R_9, R_{10} are as defined above. Preferred embodiments of the amide will not include imides which may be unstable.

The term "alkylthio" refers to an alkyl group, as defined above, having a sulfur radical attached thereto. In preferred embodiments, the "alkylthio" moiety is represented by one of -S-alkyl, -S-alkenyl, -S-alkynyl, and $-S-(CH_2)_m-R_8$, wherein m and R_8 are defined above. Representative alkylthio groups include methylthio, ethyl thio, and the like.

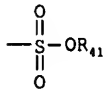
The term "carbonyl" is art recognized and includes such moieties as can be represented by the general formula:



wherein X is a bond or represents an oxygen or a sulfur, and R_{11} represents a hydrogen, an alkyl, an alkenyl, -$(CH_2)_m$-R_8 or a pharmaceutically acceptable salt, R'_{11} represents a hydrogen, an alkyl, an alkenyl or -$(CH_2)_m$-R_8, where m and R_8 are as defined above. Where X is an oxygen and R_{11} or R'_{11} is not hydrogen, the formula represents an "ester". Where X is an oxygen, and R_{11} is as defined above, the moiety is referred to herein as a carboxyl group, and particularly when R_{11} is a hydrogen, the formula represents a "carboxylic acid". Where X is an oxygen, and R'_{11} is hydrogen, the formula represents a "formate". In general, where the oxygen atom of the above formula is replaced by sulfur, the formula represents a "thiolcarbonyl" group. Where X is a sulfur and R_{11} or R'_{11} is not hydrogen, the formula represents a "thiolester." Where X is a sulfur and R_{11} is hydrogen, the formula represents a "thiolcarboxylic acid." Where X is a sulfur and R_{11}' is hydrogen, the formula represents a "thiolformate." On the other hand, where X is a bond, and R_{11} is not hydrogen, the above formula represents a "ketone" group. Where X is a bond, and R_{11} is hydrogen, the above formula represents an "aldehyde" group.

The terms "alkoxyl" or "alkoxy" as used herein refers to an alkyl group, as defined above, having an oxygen radical attached thereto. Representative alkoxyl groups include methoxy, ethoxy, propyloxy, tert-butoxy and the like. An "ether" is two hydrocarbons covalently linked by an oxygen. Accordingly, the substituent of an alkyl that renders that alkyl an ether is or resembles an alkoxyl, such as can be represented by one of -O-alkyl, -O-alkenyl, -O-alkynyl, -O-$(CH_2)_m$-R_8, where m and R_8 are described above.

The term "sulfonate" is art recognized and includes a moiety that can be represented by the general formula: :

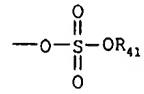


in which R_{41} is an electron pair, hydrogen, alkyl, cycloalkyl, or aryl.

The terms triflyl, tosyl, mesyl, and nonaflyl are art-recognized and refer to trifluoromethanesulfonyl, *p*-toluenesulfonyl, methanesulfonyl, and nonafluorobutanesulfonyl groups, respectively. The terms triflate, tosylate, mesylate, and nonaflate are art-recognized and refer to trifluoromethanesulfonate ester, *p*-

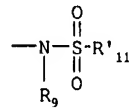
toluenesulfonate ester, methanesulfonate ester, and nonafluorobutanesulfonate ester functional groups and molecules that contain said groups, respectively.

The term "sulfate" is art recognized and includes a moiety that can be represented by the general formula:



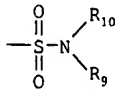
in which R_{41} is as defined above.

The term "sulfonamido" is art recognized and includes a moiety that can be represented by the general formula:



in which R_9 and R'_{11} are as defined above.

The term "sulfamoyl" is art-recognized and includes a moiety that can be represented by the general formula:

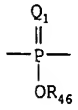


in which R_9 and R_{10} are as defined above.

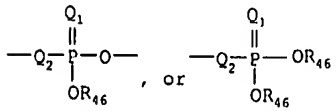
The terms "sulfoxido" or "sulfinyl", as used herein, refers to a moiety that can be represented by the general formula:

in which R_{44} is selected from the group consisting of hydrogen, alkyl, alkenyl, alkynyl, cycloalkyl, heterocyclyl, aralkyl, or aryl.

A "phosphoryl" can in general be represented by the formula:

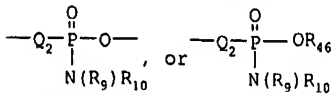


wherein Q_1 represented S or O, and R_{46} represents hydrogen, a lower alkyl or an aryl. When used to substitute, e.g., an alkyl, the phosphoryl group of the phosphorylalkyl can be represented by the general formula:



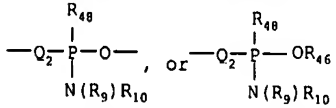
wherein Q_1 represented S or O, and each R_{46} independently represents hydrogen, a lower alkyl or an aryl, Q_2 represents O, S or N. When Q_1 is an S, the phosphoryl moiety is a "phosphorothioate".

A "phosphoramidite" can be represented in the general formula:



wherein R_9 and R_{10} are as defined above, and Q_2 represents O, S or N.

A "phosphonamidite" can be represented in the general formula:



wherein R_9 and R_{10} are as defined above, Q_2 represents O, S or N, and R_{48} represents a lower alkyl or an aryl, Q_2 represents O, S or N.

A "selenoalkyl" refers to an alkyl group having a substituted seleno group attached thereto. Exemplary "selenoethers" which may be substituted on the alkyl are selected from one of -Se-alkyl, -Se-alkenyl, -Se-alkynyl, and -Se-$(CH_2)_m$-R_8, m and R_8 being defined above.

Analogous substitutions can be made to alkenyl and alkynyl groups to produce, for example, aminoalkenyls, aminoalkynyls, amidoalkenyls, amidoalkynyls, iminoalkenyls, iminoalkynyls, thioalkenyls, thioalkynyls, carbonyl-substituted alkenyls or alkynyls.

As used herein, the definition of each expression, e.g. alkyl, m, n, etc., when it occurs more than once in any structure, is intended to be independent of its definition elsewhere in the same structure.

Certain compounds of the present invention may exist in particular geometric or stereoisomeric forms. The present invention contemplates all such compounds, including

cis- and trans-isomers, *R*- and *S*-enantiomers, diastereomers, (D)-isomers, (L)-isomers, the racemic mixtures thereof, and other mixtures thereof, as falling within the scope of the invention. Additional asymmetric carbon atoms may be present in a substituent such as an alkyl group. All such isomers, as well as mixtures thereof, are intended to be included in this invention.

If, for instance, a particular enantiomer of a compound of the present invention is desired, it may be prepared by asymmetric synthesis, or by derivation with a chiral auxiliary, where the resulting diastereomeric mixture is separated and the auxiliary group cleaved to provide the pure desired enantiomers. Alternatively, where the molecule contains a basic functional group, such as amino, or an acidic functional group, such as carboxyl, diastereomeric salts are formed with an appropriate optically-active acid or base, followed by resolution of the diastereomers thus formed by fractional crystallization or chromatographic means well known in the art, and subsequent recovery of the pure enantiomers.

Contemplated equivalents of the compounds described above include compounds which otherwise correspond thereto, and which have the same general properties thereof (e.g. the ability to inhibit hedgehog signaling), wherein one or more simple variations of substituents are made which do not adversely affect the efficacy of the compound. In general, the compounds of the present invention may be prepared by the methods illustrated in the general reaction schemes as, for example, described below, or by modifications thereof, using readily available starting materials, reagents and conventional synthesis procedures. In these reactions, it is also possible to make use of variants which are in themselves known, but are not mentioned here.

It will be understood that "substitution" or "substituted with" includes the implicit proviso that such substitution is in accordance with permitted valence of the substituted atom and the substituent, and that the substitution results in a stable compound, e.g., which does not spontaneously undergo transformation such as by rearrangement, cyclization, elimination, etc.

As used herein, the term "substituted" is contemplated to include all permissible substituents of organic compounds. In a broad aspect, the permissible substituents include acyclic and cyclic, branched and unbranched, carbocyclic and heterocyclic, aromatic and nonaromatic substituents of organic compounds. Illustrative substituents include, for example, those described herein above. The permissible substituents can be one or more and the same or different for appropriate organic compounds. For purposes of this invention, the heteroatoms such as nitrogen may have hydrogen substituents and/or any permissible substituents of organic compounds described herein which satisfy the valences

of the heteroatoms. This invention is not intended to be limited in any manner by the permissible substituents of organic compounds.

For purposes of this invention, the chemical elements are identified in accordance with the Periodic Table of the Elements, CAS version, Handbook of Chemistry and Physics, 67th Ed., 1986-87, inside cover. Also for purposes of this invention, the term "hydrocarbon" is contemplated to include all permissible compounds having at least one hydrogen and one carbon atom. In a broad aspect, the permissible hydrocarbons include acyclic and cyclic, branched and unbranched, carbocyclic and heterocyclic, aromatic and nonaromatic organic compounds which can be substituted or unsubstituted.

The phrase "protecting group" as used herein means temporary substituents which protect a potentially reactive functional group from undesired chemical transformations. Examples of such protecting groups include esters of carboxylic acids, silyl ethers of alcohols, and acetals and ketals of aldehydes and ketones, respectively. The field of protecting group chemistry has been reviewed (Greene, T.W.; Wuts, P.G.M. *Protective Groups in Organic Synthesis*, 2nd ed.; Wiley: New York, 1991).

A list of many of the abbreviations utilized by organic chemists of ordinary skill in the art appears in the first issue of each volume of the *Journal of Organic Chemistry*; this list is typically presented in a table entitled Standard List of Abbreviations. The abbreviations contained in said list, and all abbreviations utilized by organic chemists of ordinary skill in the art are hereby incorporated by reference.

The term "ED_{50}" means the dose of a drug which produces 50% of its maximum response or effect. Alternatively, the dose which produces a pre-determined response in 50% of test subjects or preparations.

The term "LD_{50}" means the dose of a drug which is lethal in 50% of test subjects.

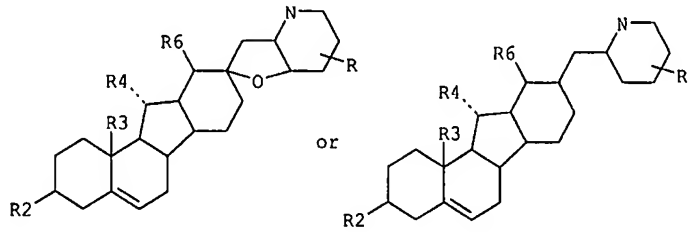
The term "therapeutic index" refers to the therapeutic index of a drug defined as LD_{50}/ED_{50}.

As used herein, "steroid hormone receptor superfamily" refers to the class of related receptors comprised of glucocorticoid, mineralocorticoid, progesterone, estrogen, estrogen-related, vitamin D3, thyroid, v-erb-A, retinoic acid and E75 (Drosophila) receptors. As used herein "steroid hormone receptor" refers to members within the steroid hormone receptor superfamily. In higher organisms, the nuclear hormone receptor superfamily includes approximately a dozen distinct genes that encode zinc finger transcription factors, each of which is specifically activated by binding a ligand such as a steroid, thyroid hormone (T3) or retinoic acid (RA).

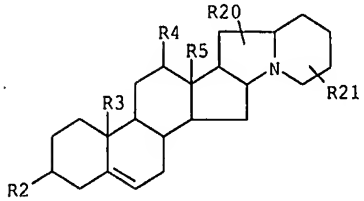
III. Exemplary Compounds of the Invention.

As described in further detail below, it is contemplated that the subject methods can be carried out using a variety of different steroidal alkaloids, as well as non-steroidal small molecules, which can be readily identified, e.g., by such drug screening assays as described herein. The above notwithstanding, in a preferred embodiment, the methods and compositions of the present invention make use of compounds having a steroidal alkaloid ring system. Steroidal alkaloids have a fairly complex nitrogen containing nucleus. Two exemplary classes of steroidal alkaloids for use in the subject methods are the Solanum type and the Veratrum type.

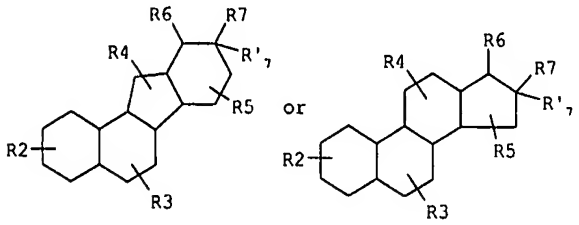
There are more than 50 naturally occuring veratrum alkaloids including veratramine, cyclopamine, cycloposine, jervine, and muldamine occurring in plants of the Veratrum spp. The Zigadenus spp., death camas, also produces several veratrum-type of steroidal alkaloids including zygacine. In general, many of the veratrum alkaloids (e.g., jervine, cyclopamine and cycloposine) consist of a modified steroid skeleton attached spiro to a furanopiperidine. A typical veratrum-type alkaloid may be represented by:



An example of the Solanum type is solanidine. This steroidal alkaloid is the nucleus (i.e. aglycone) for two important glycoalkaloids, solanine and chaconine, found in potatoes. Other plants in the Solanum family including various nightshades, Jerusalem cherries, and tomatoes also contain solanum-type glycoalkaloids. Glycoalkaloids are glycosides of alkaloids. A typical solanum-type alkaloid may be represented by:



Based on these structures, and the possibility that certain unwanted side effects can be reduced by some manipulation of the structure, a wide range of steroidal alkaloids are contemplated as potential *hedgehog* antagonists for use in the subject method. For example, compounds useful in the subject methods include steroidal alkaloids represented in the general forumlas (I) or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula I

wherein, as valence and stability permit,

R_2, R_3, R_4, and R_5, represent one or more substitutions to the ring to which each is attached, for each occurrence, independently represent hydrogen, halogens, alkyls, alkenyls, alkynyls, aryls, hydroxyl, =O, =S, alkoxyl, silyloxy, amino, nitro, thiol, amines, imines, amides, phosphoryls, phosphonates, phosphines, carbonyls, carboxyls, carboxamides, anhydrides, silyls, ethers, thioethers, alkylsulfonyls, arylsulfonyls, selenoethers, ketones, aldehydes, esters, or $-(CH_2)_m-R_8$;

R_6, R_7, and R'_7, are absent or represent, independently, halogens, alkyls, alkenyls, alkynyls, aryls, hydroxyl, =O, =S, alkoxyl, silyloxy, amino, nitro, thiol, amines, imines, amides, phosphoryls, phosphonates, phosphines, carbonyls, carboxyls, carboxamides, anhydrides, silyls, ethers, thioethers, alkylsulfonyls, arylsulfonyls, selenoethers, ketones, aldehydes, esters, or $-(CH_2)_m-R_8$, or

R_6 and R_7, or R_7 and R'_7, taken together form a ring or polycyclic ring, e.g., which is susbstituted or unsubstituted,

with the proviso that at least one of R_6, R_7, or R'_7 is present and includes a primary or secondary amine;

R_8 represents an aryl, a cycloalkyl, a cycloalkenyl, a heterocycle, or a polycycle; and

m is an integer in the range 0 to 8 inclusive.

In preferred embodiments,

R_2 and R_3, for each occurrence, is an -OH, alkyl, -O-alkyl, -C(O)-alkyl, or $-C(O)-R_8$;

R_4, for each occurrence, is an absent, or represents -OH, =O, alkyl, -O-alkyl, -C(O)-alkyl, or $-C(O)-R_8$;

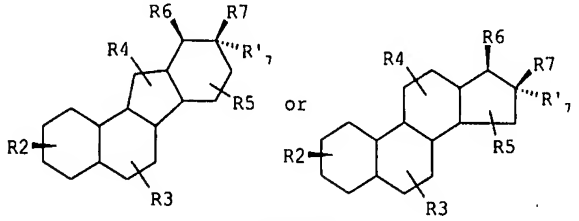
R_6, R_7, and R'_7 each independently represent, hydrogen, alkyls, alkenyls, alkynyls, amines, imines, amides, carbonyls, carboxyls, carboxamides, ethers, thioethers, esters, or $-(CH_2)_m-R_8$, or

R_7, and R'_7 taken together form a furanopiperidine, such as perhydrofuro[3,2-b]pyridine, a pyranopiperidine, a quinoline, an indole, a pyranopyrrole, a naphthyridine, a thiofuranopiperidine, or a thiopyranopiperidine

with the proviso that at least one of R_6, R_7, or R'_7 is present and includes a primary or secondary amine;

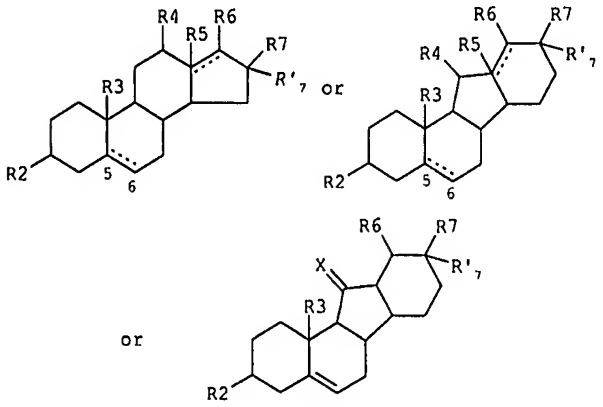
R_8 represents an aryl, a cycloalkyl, a cycloalkenyl, a heterocycle, or a polycycle, and preferably R_8 is a piperidine, pyrimidine, morpholine, thiomorpholine, pyridazine,

In certain preferred embodiments, the definitions outlined above apply, and the subject compounds are represented by general formula Ia or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula Ia

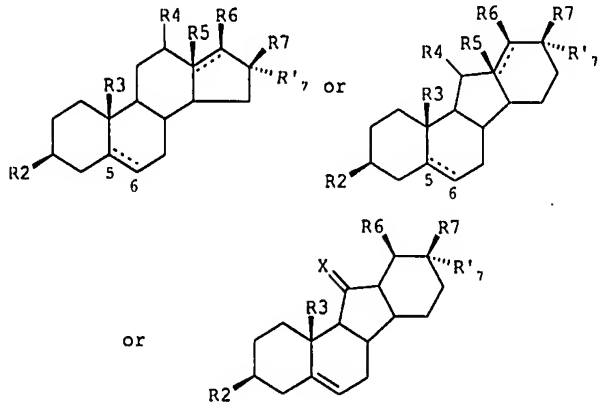
In preferred embodiments, the subject hedgehog antagonists can be represented in one of the following general formulas (II) or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula II

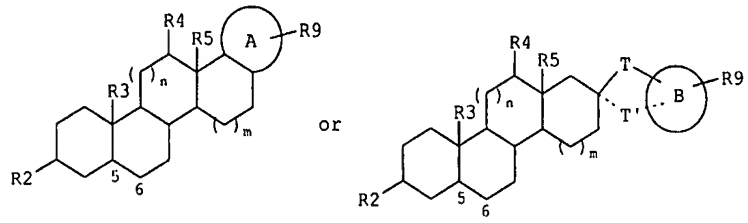
wherein R_2, R_3, R_4, R_5, R_6, R_7, and R'_7 are as defined above, and X represents O or S, though preferably O.

In certain preferred embodiments, the definitions outlined above apply, and the subject compounds are represented by general formula IIa or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula IIa

In certain embodiments, the subject hedgehog antagonists are represented by the general formula (III) or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula III

wherein

R_2, R_3, R_4, R_5 and R_8 are as defined above;

A and B represent monocyclic or polycyclic groups;

T represent an alkyl, an aminoalkyl, a carboxyl, an ester, an amide, ether or amine linkage of 1-10 bond lengths;

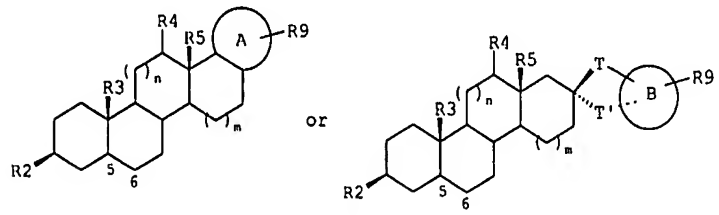
T' is absent, or represents an alkyl, an aminoalkyl, a carboxyl, an ester, an amide, ether or amine linkage of 1-3 bond lengths, wherein if T and T' are present together, than T and T' taken together with the ring A or B form a covelently closed ring of 5-8 ring atoms;

R9 represent one or more substitutions to the ring A or B, which for each occurrence, independently represent halogens, alkyls, alkenyls, alkynyls, aryls, hydroxyl, =O, =S, alkoxyl, silyloxy, amino, nitro, thiol, amines, imines, amides, phosphoryls, phosphonates, phosphines, carbonyls, carboxyls, carboxamides, anhydrides, silyls, ethers, thioethers, alkylsulfonyls, arylsulfonyls, selenoethers, ketones, aldehydes, esters, or -$(CH_2)_m$-R_8; and

n and m are, independently, zero, 1 or 2;

with the proviso that A and R_9, or T, T' B and R_9, taken together include at least one primary or secondary amine.

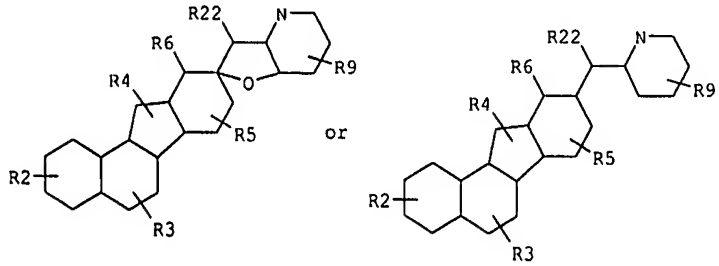
In certain preferred embodiments, the definitions outlined above apply, and the subject compounds are represented by general formula IIIa or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula IIIa

For example, the subject methods can utilize hedgehog antagonists based on the veratrum-type steroidal alkaloids jervine, cyclopamine, cycloposine, mukiamine or veratramine, e.g., which may be represented in the general formula (IV) or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:

:



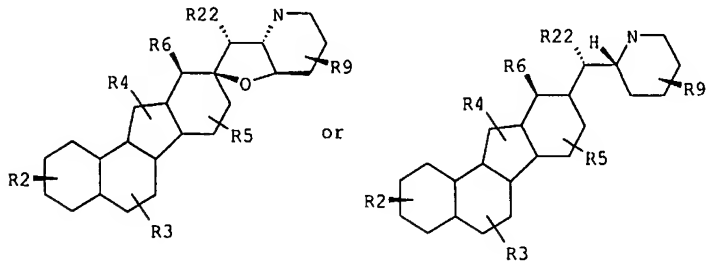
Formula IV

wherein

R_2, R_3, R_4, R_5, R_6 and R_9 are as defined above;

R_{22} is absent or represents an alkyl, an alkoxyl or -OH.

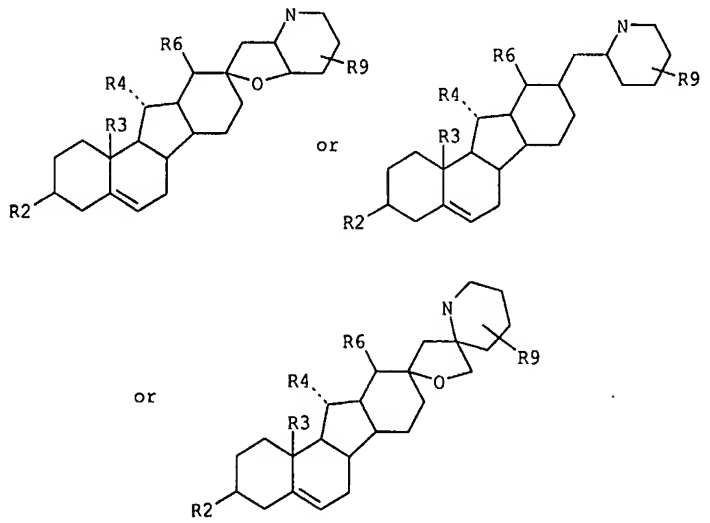
In certain preferred embodiments, the definitions outlined above apply, and the subject compounds are represented by general formula IVa or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula IVa

In even more preferred embodments, the subject antagonists are represented in the formulas (V) or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:

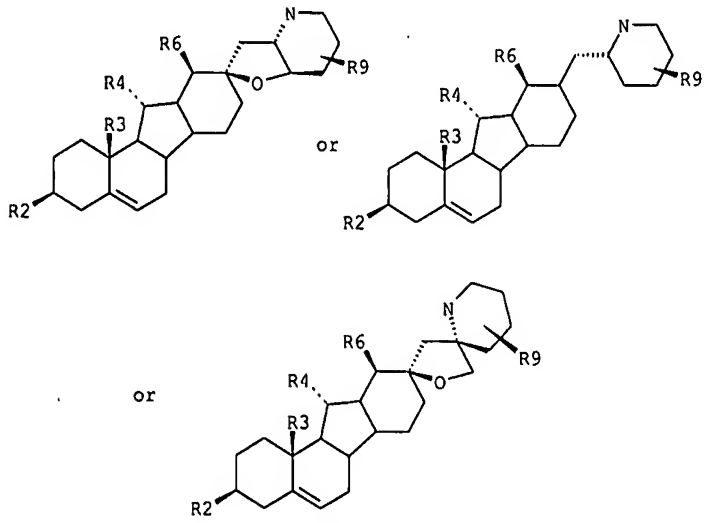
:



Formula V

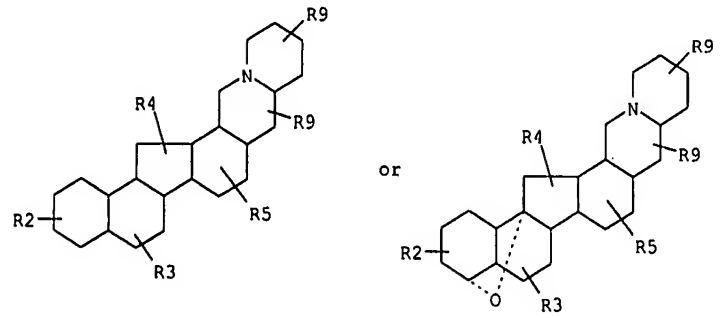
wherein R_2, R_3, R_4, R_6 and R_9 are as defined above;

In certain preferred embodiments, the definitions outlined above apply, and the subject compounds are represented by general formula Va or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula Va

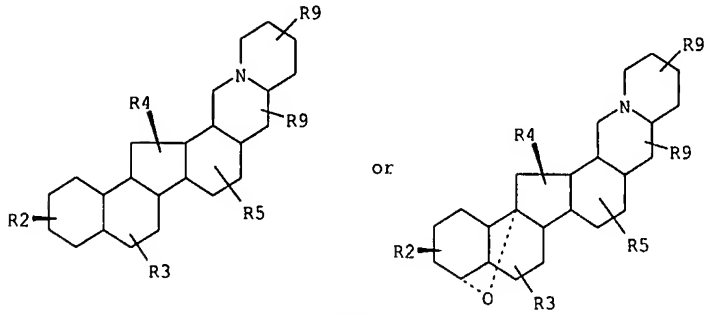
Another class of hedgehog antagonists can be based on the veratrum-type steroidal alkaloids resmebling verticine and zygacine, e.g., represented in the general formulas (VI) or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula VI

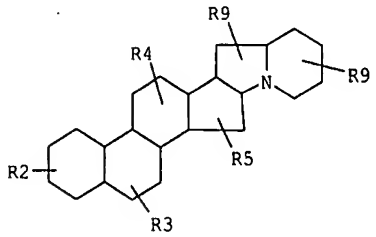
wherein R_2, R_3, R_4, R_5 and R_9 are as defined above.

In certain preferred embodiments, the definitions outlined above apply, and the subject compounds are represented by general formula VIa or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula VIa

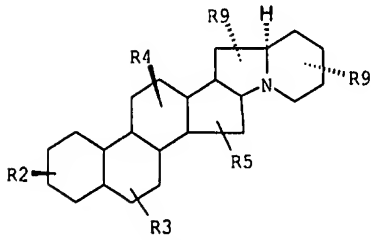
Still another class of potential hedgehog antagonists are based on the solanum-type steroidal alkaloids, e.g., solanidine, which may be represented in the general formula (VII) or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula VII

wherein R_2, R_3, R_4, R_5 and R_9 are as defined above.

In certain preferred embodiments, the definitions outlined above apply, and the subject compounds are represented by general formula VIIa or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Fromula VIIa

In certain embodiments, the subject antagonists can be chosen on the basis of their selectively for the hedgehog pathway. This selectivity can for the hedgehog pathway versus other steroid-mediated pathways (such as testosterone or estrogen mediated activities), as well as selectivity for particular hedgehog pathways, e.g., which isotype specific for hedgehog (e.g., Shh, Ihh, Dhh) or the patched receptor (e.g., ptc-1, ptc-2). For instance, the subject method may employ steroidal alkaloids which do not substantially interfere with the biological activity of such steroids as aldosterone, androstane, androstene, androstenedione, androsterone, cholecalciferol, cholestane, cholic acid, corticosterone, cortisol, cortisol acetate, cortisone, cortisone acetate, deoxycorticosterone, digitoxigenin, ergocalciferol, ergosterol, estradiol-17-α, estradiol-17-β, estriol, estrane, estrone, hydrocortisone, lanosterol, lithocholic acid, mestranol, β-methasone, prednisone, pregnane, pregnenolone, progesterone, spironolactone, testosterone, triamcinolone and their derivatives, at least so far as those activities are unrelated to ptc related signaling.

In one embodiment, the subject steroidal alkaloid for use in the present method has a k_d for members of the nuclear hormone receptor superfamily of greater than 1μM, and more preferably greater than 1mM, e.g., it does not bind estrogen, testosterone receptors or the like. Preferably, the subject hedgehog antagonist has no estrogenic activity at physiological concentrations (e.g., in the range of 1 ng-1 mg/kg), e.g. an ED_{50} greater than 1mM.

In this manner, untoward side effects which may be associated certain members of the steroidal alkaloid class can be reduced. For example, using the drug screening assays described herein, the application of combinatorial and medicinal chemistry techniques to the steroidal alkaloids provides a means for reducing such unwanted negative side effects including personality changes, shortened life spans, cardiovascular diseases and vascular occlusion., organ toxicity, hyperglycemia and diabetes, Cushnoid features, "wasting" syndrome, steroidal glaucoma, hypertension, peptic ulcers, and increased susceptibility to infections. For certain embodiments, it will be benefical to reduce the teratogenic activity

relative to jervine, as for example, in the use of the subject method to selectively inhibit spermatogenesis.

In preferred embodiment, the subject antagonists are steroidal alkaloids other than spirosolane, tomatidine, jervine, etc.

In certain preferred embodiments, the subject inhibitors inhibit a hedgehog signal transduction pathway with an ED_{50} of 1mM or less, more preferably of 1 μM or less, and even more preferably of 1nM or less.

In certain embodiments, the subject inhibitors inhibit a hedgehog signal transduction pathway with an ED_{50} of 1mM or less, more preferably 1 μM or less, and even more preferably 1nM or less.

In particular embodiments, the steroidal alkaloid is chosen for use because it is more selective for one hedgehog isoform over the next, e.g., 10 fold, and more preferably at least 100 or even 1000 fold more selective for one hedgehog pathway (Shh, Ihh, Dhh) over another. Likewise, a steroidal alkaloid can be chosen for use because it is more selective for one patched isoform over the next, e.g., 10 fold, and more preferably at least 100 or even 1000 fold more selective for one patched pathway (ptc-1, ptc-2) over another.

IV. Exemplary Applications of Method and Compositions

Another aspect of the present invention relates to a method of modulating a differentiated state, survival, and/or proliferation of a cell responsive to a *hedgehog* protein, or which has a phenotype involving aberrant activations of a hedgehog signaling pathway by contacting the cells with a *hedgehog* antagonist according to the subject method and as the circumstances may warrant. For instance, it is contemplated by the invention that, in light of the present finding of an apparently broad involvement of *hedgehog* proteins in the formation of ordered spatial arrangements of differentiated tissues in vertebrates, the subject method could be used as part of a process for generating and/or maintaining an array of different vertebrate tissue both *in vitro* and *in vivo*. The *hedgehog* antagonist, whether inductive or anti-inductive with respect proliferation or differentiation of a given tissue, can be, as appropriate, any of the preparations described above, including veratrum-type alkaloids and solanum-type alkaloids.

For example, the present method is applicable to cell culture techniques. *In vitro* neuronal culture systems have proved to be fundamental and indispensable tools for the study of neural development, as well as the identification of neurotrophic factors such as nerve growth factor (NGF), ciliary trophic factors (CNTF), and brain derived neurotrophic

factor (BDNF). Once a neuronal cell has become terminally-differentiated it typically will not change to another terminally differentiated cell-type. However, neuronal cells can nevertheless readily lose their differentiated state. This is commonly observed when they are grown in culture from adult tissue, and when they form a blastema during regeneration. The present method provides a means for ensuring an adequately restrictive environment in order to maintain neuronal cells at various stages of differentiation, and can be employed, for instance, in cell cultures designed to test the specific activities of other trophic factors. In such embodiments of the subject method, the cultured cells can be contacted with a hedgehog antagonist of the present invention in order to alter the rate of proliferation of neuronal stem cells in the culture and/or alter the rate of differentiation, or to maintain the integrity of a culture of certain terminally-differentiated neuronal cells by preventing loss of differentiation. In an exemplary embodiment, the subject method can be used to culture, for example, sensory neurons or, alternatively, motorneurons. Such neuronal cultures can be used as convenient assay systems as well as sources of implantable cells for therapeutic treatments. For example, *hedgehog* polypeptides may be useful in establishing and maintaining the olfactory neuron cultures described in U.S. Patent 5,318,907 and the like.

According to the present invention, large numbers of non-tumorigenic neural progenitor cells can be perpetuated *in vitro* and their rate of proliferation and/or differentiation can be effected by contact with *hedgehog* antagonists of the present invention. Generally, a method is provided comprising the steps of isolating neural progenitor cells from an animal, perpetuating these cells *in vitro* or *in vivo*, preferably in the presence of growth factors, and regulating the differentiation of these cells into particular neural phenotypes, e.g., neurons and glia, by contacting the cells with a *hedgehog* antagonist.

Progenitor cells are thought to be under a tonic inhibitory influence which maintains the progenitors in a suppressed state until their differentiation is required. However, recent techniques have been provided which permit these cells to be proliferated, and unlike neurons which are terminally differentiated and therefore non-dividing, they can be produced in unlimited number and are highly suitable for transplantation into heterologous and autologous hosts with neurodegenerative diseases.

By "progenitor" it is meant an oligopotent or multipotent stem cell which is able to divide without limit and, under specific conditions, can produce daughter cells which terminally differentiate such as into neurons and glia. These cells can be used for transplantation into a heterologous or autologous host. By heterologous is meant a host

other than the animal from which the progenitor cells were originally derived. By autologous is meant the identical host from which the cells were originally derived.

Cells can be obtained from embryonic, post-natal, juvenile or adult neural tissue from any animal. By any animal is meant any multicellular animal which contains nervous tissue. More particularly, is meant any fish, reptile, bird, amphibian or mammal and the like. The most preferable donors are mammals, especially mice and humans.

In the case of a heterologous donor animal, the animal may be euthanized, and the brain and specific area of interest removed using a sterile procedure. Brain areas of particular interest include any area from which progenitor cells can be obtained which will serve to restore function to a degenerated area of the host's brain. These regions include areas of the central nervous system (CNS) including the cerebral cortex, cerebellum, midbrain, brainstem, spinal cord and ventricular tissue, and areas of the peripheral nervous system (PNS) including the carotid body and the adrenal medulla. More particularly, these areas include regions in the basal ganglia, preferably the striatum which consists of the caudate and putamen, or various cell groups such as the globus pallidus, the subthalamic nucleus, the nucleus basalis which is found to be degenerated in Alzheimer's Disease patients, or the substantia nigra pars compacta which is found to be degenerated in Parkinson's Disease patients.

Human heterologous neural progenitor cells may be derived from fetal tissue obtained from elective abortion, or from a post-natal, juvenile or adult organ donor. Autologous neural tissue can be obtained by biopsy, or from patients undergoing neurosurgery in which neural tissue is removed, in particular during epilepsy surgery, and more particularly during temporal lobectomies and hippocampalectomies.

Cells can be obtained from donor tissue by dissociation of individual cells from the connecting extracellular matrix of the tissue. Dissociation can be obtained using any known procedure, including treatment with enzymes such as trypsin, collagenase and the like, or by using physical methods of dissociation such as with a blunt instrument. Dissociation of fetal cells can be carried out in tissue culture medium, while a preferable medium for dissociation of juvenile and adult cells is artificial cerebral spinal fluid (aCSF). Regular aCSF contains 124 mM NaCl, 5 mM KCl, 1.3 mM $MgCl_2$, 2 mM $CaCl_2$, 26 mM $NaHCO_3$, and 10 mM D-glucose. Low Ca^{2+} aCSF contains the same ingredients except for $MgCl_2$ at a concentration of 3.2 mM and $CaCl_2$ at a concentration of 0.1 mM.

Dissociated cells can be placed into any known culture medium capable of supporting cell growth, including MEM, DMEM, RPMI, F-12, and the like, containing

supplements which are required for cellular metabolism such as glutamine and other amino acids, vitamins, minerals and useful proteins such as transferrin and the like. Medium may also contain antibiotics to prevent contamination with yeast, bacteria and fungi such as penicillin, streptomycin, gentamicin and the like. In some cases, the medium may contain serum derived from bovine, equine, chicken and the like. A particularly preferable medium for cells is a mixture of DMEM and F-12.

Conditions for culturing should be close to physiological conditions. The pH of the culture media should be close to physiological pH, preferably between pH 6-8, more preferably close to pH 7, even more particularly about pH 7.4. Cells should be cultured at a temperature close to physiological temperature, preferably between 30°C-40°C, more preferably between 32°C-38°C, and most preferably between 35°C-37°C.

Cells can be grown in suspension or on a fixed substrate, but proliferation of the progenitors is preferably done in suspension to generate large numbers of cells by formation of "neurospheres" (see, for example, Reynolds et al. (1992) *Science* 255:1070-1709; and PCT Publications WO93/01275, WO94/09119, WO94/10292, and WO94/16718). In the case of propagating (or splitting) suspension cells, flasks are shaken well and the neurospheres allowed to settle on the bottom corner of the flask. The spheres are then transferred to a 50 ml centrifuge tube and centrifuged at low speed. The medium is aspirated, the cells resuspended in a small amount of medium with growth factor, and the cells mechanically dissociated and resuspended in separate aliquots of media.

Cell suspensions in culture medium are supplemented with any growth factor which allows for the proliferation of progenitor cells and seeded in any receptacle capable of sustaining cells, though as set out above, preferably in culture flasks or roller bottles. Cells typically proliferate within 3-4 days in a 37°C incubator, and proliferation can be reinitiated at any time after that by dissociation of the cells and resuspension in fresh medium containing growth factors.

In the absence of substrate, cells lift off the floor of the flask and continue to proliferate in suspension forming a hollow sphere of undifferentiated cells. After approximately 3-10 days *in vitro*, the proliferating clusters (neurospheres) are fed every 2-7 days, and more particularly every 2-4 days by gentle centrifugation and resuspension in medium containing growth factor.

After 6-7 days *in vitro*, individual cells in the neurospheres can be separated by physical dissociation of the neurospheres with a blunt instrument, more particularly by triturating the neurospheres with a pipette. Single cells from the dissociated neurospheres are suspended in culture medium containing growth factors, and differentiation of the cells

can be control in culture by plating (or resuspending) the cells in the presence of a *hedgehog* antagonist.

To further illustrate other uses of the subject *hedgehog* antagonists, it is noted that intracerebral grafting has emerged as an additional approach to central nervous system therapies. For example, one approach to repairing damaged brain tissues involves the transplantation of cells from fetal or neonatal animals into the adult brain (Dunnett et al. (1987) *J Exp Biol* 123:265-289; and Freund et al. (1985) *J Neurosci* 5:603-616). Fetal neurons from a variety of brain regions can be successfully incorporated into the adult brain, and such grafts can alleviate behavioral defects. For example, movement disorder induced by lesions of dopaminergic projections to the basal ganglia can be prevented by grafts of embryonic dopaminergic neurons. Complex cognitive functions that are impaired after lesions of the neocortex can also be partially restored by grafts of embryonic cortical cells. The subject method can be used to regulate the growth state in the culture, or where fetal tissue is used, especially neuronal stem cells, can be used to regulate the rate of differentiation of the stem cells.

Stem cells useful in the present invention are generally known. For example, several neural crest cells have been identified, some of which are multipotent and likely represent uncommitted neural crest cells, and others of which can generate only one type of cell, such as sensory neurons, and likely represent committed progenitor cells. The role of *hedgehog* antagonists employed in the present method to culture such stem cells can be to regulate differentiation of the uncommitted progenitor, or to regulate further restriction of the developmental fate of a committed progenitor cell towards becoming a terminally-differentiated neuronal cell. For example, the present method can be used *in vitro* to regulate the differentiation of neural crest cells into glial cells, schwann cells, chromaffin cells, cholinergic sympathetic or parasympathetic neurons, as well as peptidergic and serotonergic neurons. The *hedgehog* antagonists can be used alone, or can be used in combination with other neurotrophic factors which act to more particularly enhance a particular differentiation fate of the neuronal progenitor cell.

In addition to the implantation of cells cultured in the presence of the subject *hedgehog* antagonists, yet another aspect of the present invention concerns the therapeutic application of a *hedgehog* antagonist to regulate the growth state of neurons and other neuronal cells in both the central nervous system and the peripheral nervous system. The ability of *hedgehog* protein to regulate neuronal differentiation during development of the nervous system and also presumably in the adult state indicates that, in certain instances, the subject *hedgehog* antagonists can be expected to facilitate control of adult neurons with regard to maintenance, functional performance, and aging of normal cells; repair and

regeneration processes in chemically or mechanically lesioned cells; and treatment of degeneration in certain pathological conditions. In light of this understanding, the present invention specifically contemplates applications of the subject method to the treatment protocol of (prevention and/or reduction of the severity of) neurological conditions deriving from: (i) acute, subacute, or chronic injury to the nervous system, including traumatic injury, chemical injury, vascular injury and deficits (such as the ischemia resulting from stroke), together with infectious/inflammatory and tumor-induced injury; (ii) aging of the nervous system including Alzheimer's disease; (iii) chronic neurodegenerative diseases of the nervous system, including Parkinson's disease, Huntington's chorea, amylotrophic lateral sclerosis and the like, as well as spinocerebellar degenerations; and (iv) chronic immunological diseases of the nervous system or affecting the nervous system, including multiple sclerosis. The subject antagonists can be used in conjunction with a therapy involving hedgehog agonists to control the timing and rates of proliferation and/or differentiation of the affected neuronal cells.

As appropriate, the subject method can also be used in generating nerve prostheses for the repair of central and peripheral nerve damage. In particular, where a crushed or severed axon is intubulated by use of a prosthetic device, *hedgehog* agonists and antagonists can be added to the prosthetic device to regulate the rate of growth and regeneration of the dendridic processes. Exemplary nerve guidance channels are described in U.S. patents 5,092,871 and 4,955,892.

In another embodiment, the subject method can be used in the treatment of neoplastic or hyperplastic transformations such as may occur in the central nervous system. For instance, the *hedgehog* antagonists can be utilized to cause such transformed cells to become either post-mitotic or apoptotic. The present method may, therefore, be used as part of a treatment for, e.g., malignant gliomas, medulloblastomas, neuroectodermal tumors, and ependymomas.

In a preferred embodiment, the subject method can be used as part of a treatment regimen for malignant medulloblastoma and other primary CNS malignant neuroectodermal tumors.

In certain embodiments, the subject method is used as part of treatment program for medulloblastoma. Medulloblastoma, a primary brain tumor, is the most common brain tumor in children. A medulloblastoma is a primitive neuroectodermal tumor arising in the posterior fossa. They account for approximately 25% of all pediatric brain tumors (Miller). Histologically, they are small round cell tumors commonly arranged in true rosettes, but may display some differentiation to astrocytes, ependymal cells or neurons

(Rorke;Kleihues). PNET's may arise in other areas of the brain including the pineal gland (pineoblastoma) and cerebrum. Those arising in the supratentorial region generally fare worse than their PF counterparts.

Medulloblastoma/PNET's are known to recur anywhere in the CNS after resection, and can even metastasize to bone. Pretreatment evaluation should therefore include an examination of the spinal cord to exclude the possibility of "dropped metastases". Gadolinium-enhanced MRI has largely replaced myelography for this purpose, and CSF cytology is obtained postoperatively as a routine procedure.

In other embodiments, the subject method is used as part of treatment program for ependymomas. Ependymomas account for approximately 10% of the pediatric brain tumors in children. Grossly, they are tumors that arise from the ependymal lining of the ventricles and microscopically form rosettes, canals, and perivascular rosettes. In the CHOP series of 51 children reported with ependymomas, ¾ were histologically benign. Approximately 2/3 arose from the region of the 4th ventricle. One third presented in the supratentorial region. Age at presentation peaks between birth and 4 years, as demonstrated by SEER data as well as data from CHOP. Median age is about 5 years. Because so many children with this disease are babies, and because they often require multimodal therapy.

Yet another aspect of the present invention concerns the observation in the art that *hedgehog* proteins are morphogenic signals involved in other vertebrate organogenic pathways in addition to neuronal differentiation as described above, having apparent roles in other endodermal patterning, as well as both mesodermal and endodermal differentiation processes. Thus, it is contemplated by the invention that compositions comprising *hedgehog* antagonists can also be utilized for both cell culture and therapeutic methods involving generation and maintenance of non-neuronal tissue.

In one embodiment, the present invention makes use of the discovery that *hedgehog* proteins, such as *Sonic hedgehog*, are apparently involved in controlling the development of stem cells responsible for formation of the digestive tract, liver, lungs, and other organs which derive from the primitive gut. *Shh* serves as an inductive signal from the endoderm to the mesoderm, which is critical to gut morphogenesis. Therefore, for example, *hedgehog* antagonists of the instant method can be employed for regulating the development and maintenance of an artificial liver which can have multiple metabolic functions of a normal liver. In an exemplary embodiment, the subject method can be used to regulate the proliferation and differentiation of digestive tube stem cells to form hepatocyte cultures which can be used to populate extracellular matrices, or which can be

encapsulated in biocompatible polymers, to form both implantable and extracorporeal artificial livers.

In another embodiment, therapeutic compositions of *hedgehog* agonists can be utilized in conjunction with transplantation of such artificial livers, as well as embryonic liver structures, to regulate uptake of intraperitoneal implantation, vascularization, and *in vivo* differentiation and maintenance of the engrafted liver tissue.

In yet another embodiment, the subject method can be employed therapeutically to regulate such organs after physical, chemical or pathological insult. For instance, therapeutic compositions comprising *hedgehog* antagonists can be utilized in liver repair subsequent to a partial hepatectomy.

The generation of the pancreas and small intestine from the embryonic gut depends on intercellular signaling between the endodermal and mesodermal cells of the gut. In particular, the differentiation of intestinal mesoderm into smooth muscle has been suggested to depend on signals from adjacent endodermal cells. One candidate mediator of endodermally derived signals in the embryonic hindgut is Sonic hedgehog. See, for example, Apelqvist et al. (1997) Curr Biol 7:801-4. The Shh gene is expressed throughout the embryonic gut endoderm with the exception of the pancreatic bud endoderm, which instead expresses high levels of the homeodomain protein Ipf1/Pdx1 (insulin promoter factor 1/pancreatic and duodenal homeobox 1), an essential regulator of early pancreatic development. Apelqvist et al., supra, have examined whether the differential expression of Shh in the embryonic gut tube controls the differentiation of the surrounding mesoderm into specialised mesoderm derivatives of the small intestine and pancreas. To test this, they used the promoter of the Ipf1/Pdx1 gene to selectively express Shh in the developing pancreatic epithelium. In Ipf1/Pdx1- Shh transgenic mice, the pancreatic mesoderm developed into smooth muscle and interstitial cells of Cajal, characteristic of the intestine, rather than into pancreatic mesenchyme and spleen. Also, pancreatic explants exposed to Shh underwent a similar program of intestinal differentiation. These results provide evidence that the differential expression of endodermally derived Shh controls the fate of adjacent mesoderm at different regions of the gut tube.

In the context of the present invention, it is contemplated therefore that the subject hedgehog inhibitors can be used to control the regulate the proliferation and/or differentiation of pancreatic tissue both *in vivo* and *in vitro*.

There are a wide variety of pathological cell proliferative and differentiative conditions for which the *inhibitors* of the present invention may provide therapeutic benefits, with the general strategy being, for example, the correction of abberrant insulin

expression, or modulation of differentiation. More generally, however, the present invention relates to a method of inducing and/or maintaining a differentiated state, enhancing survival and/or affecting proliferation of pancreatic cells, by contacting the cells with the subject inhibitors. For instance, it is contemplated by the invention that, in light of the apparent involvement of *hedgehog protein(s)* in the formation of ordered spatial arrangements of pancreatic tissues, the subject method could be used as part of a technique to generate and/or maintain such tissue both *in vitro* and *in vivo*. For instance, modulation of the function of ptc can be employed in both cell culture and therapeutic methods involving generation and maintenance β-cells and possibly also for non-pancreatic tissue, such as in controlling the development and maintenance of tissue from the digestive tract, spleen, lungs, and other organs which derive from the primitive gut.

In an exemplary embodiment, the present method can be used in the treatment of hyperplastic and neoplastic disorders effecting pancreatic tissue, particularly those characterized by aberrant proliferation of pancreatic cells. For instance, pancreatic cancers are marked by abnormal proliferation of pancreatic cells which can result in alterations of insulin secretory capacity of the pancreas. For instance, certain pancreatic hyperplasias, such as pancreatic carcinomas, can result in hypoinsulinemia due to dysfunction of β-cells or decreased islet cell mass. To the extent that aberrant hedgehog signaling may be indicated in disease progression, the subject inhibitors, can be used to enhance regeneration of the tissue after anti-tumor therapy.

Moreover, manipulation of ptc signaling properties at different points may be useful as part of a strategy for reshaping/repairing pancreatic tissue both *in vivo* and *in vitro*. In one embodiment, the present invention makes use of the apparent involvement of the hedgehog in regulating the development of pancreatic tissue. In general, the subject method can be employed therapeutically to regulate the pancreas after physical, chemical or pathological insult. In yet another embodiment, the subject method can be applied to to cell culture techniques, and in particular, may be employed to enhance the initial generation of prosthetic pancreatic tissue devices. Manipulation of proliferation and differentiation of pancreatic tissue, for example, by altering ptc activity, can provide a means for more carefully controlling the characteristics of a cultured tissue. In an exemplary embodiment, the subject method can be used to augment production of prosthetic devices which require β-islet cells, such as may be used in the encapsulation devices described in, for example, the Aebischer et al. U.S. Patent No. 4,892,538, the Aebischer et al. U.S. Patent No. 5,106,627, the Lim U.S. Patent No. 4,391,909, and the Sefton U.S. Patent No. 4,353,888. Early progenitor cells to the pancreatic islets are multipotential, and apparently coactive all the islet-specific genes from the time they first

appear. As development proceeds, expression of islet-specific hormones, such as insulin, becomes restricted to the pattern of expression characteristic of mature islet cells. The phenotype of mature islet cells, however, is not stable in culture, as reappearence of embyonal traits in mature β-cells can be observed. By utilizing agents which alter ptc signal transduction, the the action of endogenous hedgehog protein on the differentiation path or proliferative index of the cells can be regulated.

Furthermore, manipulation of the differentiative state of pancreatic tissue can be utilized in conjunction with transplantation of artificial pancreas so as to promote implantation, vascularization, and *in vivo* differentiation and maintenance of the engrafted tissue. For instance, manipulation of *ptc* function to affect tissue differentiation can be utilized as a means of maintaining graft viability.

Bellusci et al. (1997) Development 124:53 report that Sonic *hedgehog* regulates lung mesenchymal cell proliferation in vivo. Accordingly, the present method can be used to regulate regeneration of lung tissue, e.g., in the treatment of emphysema.

Fujita et al. (1997) *Biochem Biophys Res Commun* 238:658 reported that Sonic hedgehog is expressed in human lung squamous carcinoma and adenocarcinoma cells. The expression of Sonic hedgehog was also detected in the human lung squamous carcinoma tissues, but not in the normal lung tissue of the same patient. They also observed that Sonic hedgehog stimulates the incorporation of BrdU into the carcinoma cells and stimulates their cell growth, while anti-Shh-N inhibited their cell growth. These results suggest that a Sonic hedgehog signal is involved in the cell growth of such transformed lung tissue and therefore indicates that the subject method can be used as part of a treatment of lung carcinoma and adenocarcinomas, and other proliferative disorders involving the lung epithelia.

In still another embodiment of the present invention, compositions comprising *hedgehog* antagonists can be used in the *in vitro* generation of skeletal tissue, such as from skeletogenic stem cells, as well as the *in vivo* treatment of skeletal tissue deficiencies. The present invention particularly contemplates the use of *hedgehog* antagonists to regulate the rate of chondrogenesis and/or osteogenesis. By "skeletal tissue deficiency", it is meant a deficiency in bone or other skeletal connective tissue at any site where it is desired to restore the bone or connective tissue, no matter how the deficiency originated, e.g. whether as a result of surgical intervention, removal of tumor, ulceration, implant, fracture, or other traumatic or degenerative conditions.

For instance, the method of the present invention can be used as part of a regimen for restoring cartilage function to a connective tissue. Such methods are useful in, for

example, the repair of defects or lesions in cartilage tissue which is the result of degenerative wear such as that which results in arthritis, as well as other mechanical derangements which may be caused by trauma to the tissue, such as a displacement of torn meniscus tissue, meniscectomy, a laxation of a joint by a torn ligament, malignment of joints, bone fracture, or by hereditary disease. The present reparative method is also useful for remodeling cartilage matrix, such as in plastic or reconstructive surgery, as well as periodontal surgery. The present method may also be applied to improving a previous reparative procedure, for example, following surgical repair of a meniscus, ligament, or cartilage. Furthermore, it may prevent the onset or exacerbation of degenerative disease if applied early enough after trauma.

In one embodiment of the present invention, the subject method comprises treating the afflicted connective tissue with a therapeutically sufficient amount of a *hedgehog* antagonist, particularly an antagonist selective for Indian *hedgehog*, to regulate a cartilage repair response in the connective tissue by managing the rate of differentiation and/or proliferation of chondrocytes embedded in the tissue. Such connective tissues as articular cartilage, interarticular cartilage (menisci), costal cartilage (connecting the true ribs and the sternum), ligaments, and tendons are particularly amenable to treatment in reconstructive and/or regenerative therapies using the subject method. As used herein, regenerative therapies include treatment of degenerative states which have progressed to the point of which impairment of the tissue is obviously manifest, as well as preventive treatments of tissue where degeneration is in its earliest stages or imminent.

In an illustrative embodiment, the subject method can be used as part of a therapeutic intervention in the treatment of cartilage of a diarthroidal joint, such as a knee, an ankle, an elbow, a hip, a wrist, a knuckle of either a finger or toe, or a tempomandibular joint. The treatment can be directed to the meniscus of the joint, to the articular cartilage of the joint, or both. To further illustrate, the subject method can be used to treat a degenerative disorder of a knee, such as which might be the result of traumatic injury (e.g., a sports injury or excessive wear) or osteoarthritis. The subject antagonists may be administered as an injection into the joint with, for instance, an arthroscopic needle. In some instances, the injected agent can be in the form of a hydrogel or other slow release vehicle described above in order to permit a more extended and regular contact of the agent with the treated tissue.

The present invention further contemplates the use of the subject method in the field of cartilage transplantation and prosthetic device therapies. However, problems arise, for instance, because the characteristics of cartilage and fibrocartilage varies between different tissue: such as between articular, meniscal cartilage, ligaments, and tendons,

between the two ends of the same ligament or tendon, and between the superficial and deep parts of the tissue. The zonal arrangement of these tissues may reflect a gradual change in mechanical properties, and failure occurs when implanted tissue, which has not differentiated under those conditions, lacks the ability to appropriately respond. For instance, when meniscal cartilage is used to repair anterior cruciate ligaments, the tissue undergoes a metaplasia to pure fibrous tissue. By regulating the rate of chondrogenesis, the subject method can be used to particularly address this problem, by helping to adaptively control the implanted cells in the new environment and effectively resemble hypertrophic chondrocytes of an earlier developmental stage of the tissue.

In similar fashion, the subject method can be applied to enhancing both the generation of prosthetic cartilage devices and to their implantation. The need for improved treatment has motivated research aimed at creating new cartilage that is based on collagen-glycosaminoglycan templates (Stone et al. (1990) *Clin Orthop Relat Red* 252:129), isolated chondrocytes (Grande et al. (1989) *J Orthop Res* 7:208; and Takigawa et al. (1987) *Bone Miner* 2:449), and chondrocytes attached to natural or synthetic polymers (Walitani et al. (1989) *J Bone Jt Surg* 71B:74; Vacanti et al. (1991) *Plast Reconstr Surg* 88:753; von Schroeder et al. (1991) *J Biomed Mater Res* 25:329; Freed et al. (1993) *J Biomed Mater Res* 27:11; and the Vacanti et al. U.S. Patent No. 5,041,138). For example, chondrocytes can be grown in culture on biodegradable, biocompatible highly porous scaffolds formed from polymers such as polyglycolic acid, polylactic acid, agarose gel, or other polymers which degrade over time as function of hydrolysis of the polymer backbone into innocuous monomers. The matrices are designed to allow adequate nutrient and gas exchange to the cells until engraftment occurs. The cells can be cultured *in vitro* until adequate cell volume and density has developed for the cells to be implanted. One advantage of the matrices is that they can be cast or molded into a desired shape on an individual basis, so that the final product closely resembles the patient's own ear or nose (by way of example), or flexible matrices can be used which allow for manipulation at the time of implantation, as in a joint.

In one embodiment of the subject method, the implants are contacted with a *hedgehog* antagonist during certain stages of the culturing process in order to manage the rate of differentiation of chondrocytes and the formation of hypertrophic chrondrocytes in the culture.

In another embodiment, the implanted device is treated with a *hedgehog* antagonist in order to actively remodel the implanted matrix and to make it more suitable for its intended function. As set out above with respect to tissue transplants, the artificial transplants suffer from the same deficiency of not being derived in a setting which is

comparable to the actual mechanical environment in which the matrix is implanted. The ability to regulate the chondrocytes in the matrix by the subject method can allow the implant to acquire characteristics similar to the tissue for which it is intended to replace.

In yet another embodiment, the subject method is used to enhance attachment of prosthetic devices. To illustrate, the subject method can be used in the implantation of a periodontal prosthesis, wherein the treatment of the surrounding connective tissue stimulates formation of periodontal ligament about the prosthesis.

In still further embodiments, the subject method can be employed as part of a regimen for the generation of bone (osteogenesis) at a site in the animal where such skeletal tissue is deficient. Indian hedgehog is particularly associated with the hypertrophic chondrocytes that are ultimately replaced by osteoblasts. For instance, administration of a *hedgehog* antagonists of the present invention can be employed as part of a method for regulating the rate of bone loss in a subject. For example, preparations comprising *hedgehog* antagonists can be employed, for example, to control endochondral ossification in the formation of a "model" for ossification.

In yet another embodiment of the present invention, a *hedgehog* antagonist can be used to regulate spermatogenesis. The *hedgehog* proteins, particularly Dhh, have been shown to be involved in the differentiation and/or proliferation and maintenance of testicular germ cells. Dhh expression is initiated in Sertoli cell precursors shortly after the activation of Sry and persists in the testis into the adult. Males are viable but infertile, owing to a complete absence of mature sperm. Examination of the developing testis in different genetic backgrounds suggests that Dhh regulates both early and late stages of spermatogenesis. Bitgood et al. (1996) Curr Biol 6:298. The subject method can be utilized to block the action of a naturally-occurring *hedgehog* protein. In a preferred embodiment, the *hedgehog* antagonist inhibits the biological activity of Desert *hedgehog* with respect to spermatogenesis, and can be used as a contraceptive. In similar fashion, *hedgehog* antagonists of the subject method are potentially useful for modulating normal ovarian function.

The subject method also has wide applicability to the treatment or prophylaxis of disorders afflicting epithelial tissue, as well as in cosmetic uses. In general, the method can be characterized as including a step of administering to an animal an amount of a hedgehog antagonist effective to alter the growth state of a treated epithelial tissue. The mode of administration and dosage regimens will vary depending on the epithelial tissue(s) which is to be treated. For example, topical formulations will be preferred where the treated tissue is epidermal tissue, such as dermal or mucosal tissues.

A method which "promotes the healing of a wound" results in the wound healing more quickly as a result of the treatment than a similar wound heals in the absence of the treatment. "Promotion of wound healing" can also mean that the method regulates the proliferation and/or growth of, *inter alia*, keratinocytes, or that the wound heals with less scarring, less wound contraction, less collagen deposition and more superficial surface area. In certain instances, "promotion of wound healing" can also mean that certain methods of wound healing have improved success rates, (e.g. the take rates of skin grafts,) when used together with the method of the present invention.

Despite significant progress in reconstructive surgical techniques, scarring can be an important obstacle in regaining normal function and appearance of healed skin. This is particularly true when pathologic scarring such as keloids or hypertrophic scars of the hands or face causes functional disability or physical deformity. In the severest circumstances, such scarring may precipitate psychosocial distress and a life of economic deprivation. Wound repair includes the stages of hemostasis, inflammation, proliferation, and remodeling. The proliferative stage involves multiplication of fibroblasts and endothelial and epithelial cells. Through the use of the subject method, the rate of proliferation of epithelial cells in and proximal to the wound can be controlled in order to accelerate closure of the wound and/or minimize the formation of scar tissue.

The present treatment can also be effective as part of a therapeutic regimen for treating oral and paraoral ulcers, e.g. resulting from radiation and/or chemotherapy. Such ulcers commonly develop within days after chemotherapy or radiation therapy. These ulcers usually begin as small, painful irregularly shaped lesions usually covered by a delicate gray necrotic membrane and surrounded by inflammatory tissue. In many instances, lack of treatment results in proliferation of tissue around the periphery of the lesion on an inflammatory basis. For instance, the epithelium bordering the ulcer usually demonstrates proliferative activity, resulting in loss of continuity of surface epithelium. These lesions, because of their size and loss of epithelial integrity, dispose the body to potential secondary infection. Routine ingestion of food and water becomes a very painful event and, if the ulcers proliferate throughout the alimentary canal, diarrhea usually is evident with all its complicating factors. According to the present invention, a treatment for such ulcers which includes application of an hedgehog antagonist can reduce the abnormal proliferation and differentiation of the affected epithelium, helping to reduce the severity of subsequent inflammatory events.

The subject method and compositions can also be used to treat wounds resulting from dermatological diseases, such as lesions resulting from autoimmune disorders such as psoriasis. Atopic dermititis refers to skin trauma resulting from allergies associated with

an immune response caused by allergens such as pollens, foods, dander, insect venoms and plant toxins.

In other embodiments, antiproliferative preparations of hedgehog antagonists can be used to inhibit lens epithelial cell proliferation to prevent post-operative complications of extracapsular cataract extraction. Cataract is an intractable eye disease and various studies on a treatment of cataract have been made. But at present, the treatment of cataract is attained by surgical operations. Cataract surgery has been applied for a long time and various operative methods have been examined. Extracapsular lens extraction has become the method of choice for removing cataracts. The major medical advantages of this technique over intracapsular extraction are lower incidence of aphakic cystoid macular edema and retinal detachment. Extracapsular extraction is also required for implantation of posterior chamber type intraocular lenses which are now considered to be the lenses of choice in most cases.

However, a disadvantage of extracapsular cataract extraction is the high incidence of posterior lens capsule opacification, often called after-cataract, which can occur in up to 50% of cases within three years after surgery. After-cataract is caused by proliferation of equatorial and anterior capsule lens epithelial cells which remain after extracapsular lens extraction. These cells proliferate to cause Sommerling rings, and along with fibroblasts which also deposit and occur on the posterior capsule, cause opacification of the posterior capsule, which interferes with vision. Prevention of after-cataract would be preferable to treatment. To inhibit secondary cataract formation, the subject method provides a means for inhibiting proliferation of the remaining lens epithelial cells. For example, such cells can be induced to remain quiescent by instilling a solution containing an hedgehog antagonist preparation into the anterior chamber of the eye after lens removal. Furthermore, the solution can be osmotically balanced to provide minimal effective dosage when instilled into the anterior chamber of the eye, thereby inhibiting subcapsular epithelial growth with some specificity.

The subject method can also be used in the treatment of corneopathies marked by corneal epithelial cell proliferation, as for example in ocular epithelial disorders such as epithelial downgrowth or squamous cell carcinomas of the ocular surface.

Levine et al. (1997) J Neurosci 17:6277 show that hedgehog proteins can regulate mitogenesis and photoreceptor differentiation in the vertebrate retina, and Ihh is a candidate factor from the pigmented epithelium to promote retinal progenitor proliferation and photoreceptor differentiation. Likewise, Jensen et al. (1997) Development 124:363 demonstrated that treatment of cultures of perinatal mouse retinal cells with the amino-terminal fragment of Sonic hedgehog protein results in an increase in the proportion of

cells that incorporate bromodeoxuridine, in total cell numbers, and in rod photoreceptors, amacrine cells and Muller glial cells, suggesting that Sonic hedgehog promotes the proliferation of retinal precursor cells. Thus, the subject method can be used in the treatment of proliferative diseases of retinal cells and regulate photoreceptor differentiation.

Yet another aspect of the present invention relates to the use of the subject method to control hair growth. Hair is basically composed of keratin, a tough and insoluble protein; its chief strength lies in its disulphide bond of cystine. Each individual hair comprises a cylindrical shaft and a root, and is contained in a follicle, a flask-like depression in the skin. The bottom of the follicle contains a finger-like projection termed the papilla, which consists of connective tissue from which hair grows, and through which blood vessels supply the cells with nourishment. The shaft is the part that extends outwards from the skin surface, whilst the root has been described as the buried part of the hair. The base of the root expands into the hair bulb, which rests upon the papilla. Cells from which the hair is produced grow in the bulb of the follicle; they are extruded in the form of fibers as the cells proliferate in the follicle. Hair "growth" refers to the formation and elongation of the hair fiber by the dividing cells.

As is well known in the art, the common hair cycle is divided into three stages: anagen, catagen and telogen. During the active phase (anagen) , the epidermal stem cells of the dermal papilla divide rapidly. Daughter cells move upward and differentiate to form the concentric layers of the hair itself. The transitional stage, catagen, is marked by the cessation of mitosis of the stem cells in the follicle. The resting stage is known as telogen, where the hair is retained within the scalp for several weeks before an emerging new hair developing below it dislodges the telogen-phase shaft from its follicle. From this model it has become clear that the larger the pool of dividing stem cells that differentiate into hair cells, the more hair growth occurs. Accordingly, methods for increasing or reducing hair growth can be carried out by potentiating or inhibiting, respectively, the proliferation of these stem cells.

In certain embodimemts, the subject method can be employed as a way of reducing the growth of human hair as opposed to its conventional removal by cutting, shaving, or depilation. For instance, the present method can be used in the treatment of trichosis characterized by abnormally rapid or dense growth of hair, e.g. hypertrichosis. In an exemplary embodiment, hedgehog antagonists can be used to manage hirsutism, a disorder marked by abnormal hairiness. The subject method can also provide a process for extending the duration of depilation.

Moreover, because a hedgehog antagonist will often be cytostatic to epithelial cells, rather than cytotoxic, such agents can be used to protect hair follicle cells from cytotoxic agents which require progression into S-phase of the cell-cycle for efficacy, e.g. radiation-induced death. Treatment by the subject method can provide protection by causing the hair follicle cells to become quiescent, e.g., by inhibiting the cells from entering S phase, and thereby preventing the follicle cells from undergoing mitotic catastrophe or programmed cell death. For instance, hedgehog antagonists can be used for patients undergoing chemo- or radiation-therapies which ordinarily result in hair loss. By inhibiting cell-cycle progression during such therapies, the subject treatment can protect hair follicle cells from death which might otherwise result from activation of cell death programs. After the therapy has concluded, the instant method can also be removed with concommitant relief of the inhibition of follicle cell proliferation.

The subject method can also be used in the treatment of folliculitis, such as folliculitis decalvans, folliculitis ulerythematosa reticulata or keloid folliculitis. For example, a cosmetic prepration of an hedgehog antagonist can be applied topically in the treatment of pseudofolliculitis, a chronic disorder occurring most often in the submandibular region of the neck and associated with shaving, the characteristic lesions of which are erythematous papules and pustules containing buried hairs.

In another aspect of the invention, the subject method can be used to induce differentiation of epithelially-derived tissue. Such forms of these molecules can provide a basis for differentiation therapy for the treatment of hyperplastic and/or neoplastic conditions involving epithelial tissue. For example, such preparations can be used for the treatment of cutaneous diseases in which there is abnormal proliferation or growth of cells of the skin.

For instance, the pharmaceutical preparations of the invention are intended for the treatment of hyperplastic epidermal conditions, such as keratosis, as well as for the treatment of neoplastic epidermal conditions such as those characterized by a high proliferation rate for various skin cancers, as for example basal cell carcinoma or squamous cell carcinoma. The subject method can also be used in the treatment of autoimmune diseases affecting the skin, in particular, of dermatological diseases involving morbid proliferation and/or keratinization of the epidermis, as for example, caused by psoriasis or atopic dermatosis.

Many common diseases of the skin, such as psoriasis, squamous cell carcinoma, keratoacanthoma and actinic keratosis are characterized by localized abnormal proliferation and growth. For example, in psoriasis, which is characterized by scaly, red,

elevated plaques on the skin, the keratinocytes are known to proliferate much more rapidly than normal and to differentiate less completely.

In one embodiment, the preparations of the present invention are suitable for the treatment of dermatological ailments linked to keratinization disorders causing abnormal proliferation of skin cells, which disorders may be marked by either inflammatory or non-inflammatory components. To illustrate, therapeutic preparations of a hedgehog antagonist, e.g., which promotes quiescense or differentiation can be used to treat varying forms of psoriasis, be they cutaneous, mucosal or ungual. Psoriasis, as described above, is typically characterized by epidermal keratinocytes which display marked proliferative activation and differentiation along a "regenerative" pathway. Treatment with an antiproliferative embodiment of the subject method can be used to reverse the pathological epidermal activiation and can provide a basis for sustained remission of the disease.

A variety of other keratotic lesions are also candidates for treatment with the subject method. Actinic keratoses, for example, are superficial inflammatory premalignant tumors arising on sun-exposed and irradiated skin. The lesions are erythematous to brown with variable scaling. Current therapies include excisional and cryosurgery. These treatments are painful, however, and often produce cosmetically unacceptable scarring. Accordingly, treatment of keratosis, such as actinic keratosis, can include application, preferably topical, of a hedgehog antagonist composition in amounts sufficient to inhibit hyperproliferation of epidermal/epidermoid cells of the lesion.

Acne represents yet another dermatologic ailment which may be treated by the subject method. Acne vulgaris, for instance, is a multifactorial disease most commonly occurring in teenagers and young adults, and is characterized by the appearance of inflammatory and noninflammatory lesions on the face and upper trunk. The basic defect which gives rise to acne vulgaris is hypercornification of the duct of a hyperactive sebaceous gland. Hypercornification blocks the normal mobility of skin and follicle microorganisms, and in so doing, stimulates the release of lipases by Propinobacterium acnes and *Staphylococcus epidermidis* bacteria and *Pitrosporum ovale*, a yeast. Treatment with an antiproliferative hedgehog antagonist, particularly topical preparations, may be useful for preventing the transitional features of the ducts, e.g. hypercornification, which lead to lesion formation. The subject treatment may further include, for example, antibiotics, retinoids and antiandrogens.

The present invention also provides a method for treating various forms of dermatitis. Dermatitis is a descriptive term referring to poorly demarcated lesions which are either pruritic, erythematous, scaley, blistered, weeping, fissured or crusted. These lesions arise from any of a wide variety of causes. The most common types of dermatitis

are atopic, contact and diaper dermatitis. For instance, seborrheic dermatitis is a chronic, usually pruritic, dermatitis with erythema, dry, moist, or greasy scaling, and yellow crusted patches on various areas, especially the scalp, with exfoliation of an excessive amount of dry scales. The subject method can also be used in the treatment of stasis dermatitis, an often chronic, usually eczematous dermatitis. Actinic dermatitis is dermatitis that due to exposure to actinic radiation such as that from the sun, ultraviolet waves or x- or gamma-radiation. According to the present invention, the subject method can be used in the treatment and/or prevention of certain symptoms of dermatitis caused by unwanted proliferation of epithelial cells. Such therapies for these various forms of dermatitis can also include topical and systemic corticosteroids, antipuritics, and antibiotics.

Ailments which may be treated by the subject method are disorders specific to non-humans, such as mange.

In still another embodiment, the subject method can be used in the treatment of human cancers, particularly basal cell carcinomas and other tumors of epithelial tissues such as the skin. For example, hedgehog antagonists can be employed, in the subject method, as part of a treatment for basal cell nevus syndrome (BCNS), and other other human carcinomas, adenocarcinomas, sarcomas and the like.

In a preferred embodiment, the subject method is used as part of a treatment or prophylaxis regimen for treating (or preventing) basal cell carcinoma. The deregulation of the *ptc* signaling pathway may be a general feature of basal cell carcinomas caused by *ptc* mutations. Consistent overexpression of human *ptc* mRNA has been described in tumors of familial and sporadic BCCs, determined by in situ hybridization. Mutations that inactivate *ptc* may be expected to result in overexpression of mutant *Ptc*, because *ptc* displays negative autoregulation. Prior research demonstrates that overexpression of hedgehog proteins can also lead to tumorigenesis. That sonic hedgehog (*Shh*) has a role in tumorigenesis in the mouse has been suggested by our research in which transgenic mice overexpressing *Shh* in the skin developed features of BCNS, including multiple BCC-like epidermal proliferations over the entire skin surface, after only a few days of skin development. A mutation in the *Shh* human gene from a BCC was also described; it was suggested that *Shh* or other Hh genes in humans could act as dominant oncogenes in humans. Sporadic *ptc* mutations have also been observed in BCCs from otherwise normal individuals, some of which are UV-signature mutations. In one recent study of sporadic BCCs, five UV-signature type mutations, either CT or CCTT changes, were found out of fifteen tumors determined to contain *ptc* mutations. Another recent analysis of sporadic *ptc* mutations in BCCs and neuroectodermal tumors revealed one CT change in one of three

ptc mutations found in the BCCs. See, for example, Goodrich et al. (1997) Science 277:1109-13; Xie et al. (1997) Cancer Res 57:2369-72; Oro et al. (1997) Science 276:817-21; Xie et al. (1997) Genes Chromosomes Cancer 18:305-9; Stone et al. (1996) Nature 384:129-34; and Johnson et al. (1996) Science 272:1668-71.

The subject method can also be used to treatment patients with BCNS, e.g., to prevent BCC or other effects of the disease which may be the result of ptc loss-of-function or smoothened gain-of-function. Basal cell nevus syndrome is a rare autosomal dominant disorder characterized by multiple BCCs that appear at a young age. BCNS patients are very susceptible to the development of these tumors; in the second decade of life, large numbers appear, mainly on sun-exposed areas of the skin. This disease also causes a number of developmental abnormalities, including rib, head and face alterations, and sometimes polydactyly, syndactyly, and spina bifida. They also develop a number of tumor types in addition to BCCs: fibromas of the ovaries and heart, cysts of the skin and jaws, and in the central nervous system, medulloblastomas and meningiomas. The subject method can be used to prevent or treat such tumor types. Studies of BCNS patients show that they have both genomic and sporadic mutations in the *ptc* gene, suggesting that these mutations are the ultimate cause of this disease.

In one aspect, the present invention provides pharmaceutical preparations and methods for controlling the formation of megakaryocyte-derived cells and/or controlling the functional performance of megakaryocyte-derived cells. For instance, certain of the compositions disclosed herein may be applied to the treatment or prevention of a variety hyperplastic or neoplastic conditions affecting platelets.

The *hedgehog* antagonists for use in the subject method may be conveniently formulated for administration with a biologically acceptable medium, such as water, buffered saline, polyol (for example, glycerol, propylene glycol, liquid polyethylene glycol and the like) or suitable mixtures thereof. The optimum concentration of the active ingredient(s) in the chosen medium can be determined empirically, according to procedures well known to medicinal chemists. As used herein, "biologically acceptable medium" includes any and all solvents, dispersion media, and the like which may be appropriate for the desired route of administration of the pharmaceutical preparation. The use of such media for pharmaceutically active substances is known in the art. Except insofar as any conventional media or agent is incompatible with the activity of the *hedgehog* antagonist, its use in the pharmaceutical preparation of the invention is contemplated. Suitable vehicles and their formulation inclusive of other proteins are described, for example, in the book *Remington's Pharmaceutical Sciences* (Remington's

Pharmaceutical Sciences. Mack Publishing Company, Easton, Pa., USA 1985). These vehicles include injectable "deposit formulations".

Pharmaceutical formulations of the present invention can also include veterinary compositions, e.g., pharmaceutical preparations of the *hedgehog* antagonists suitable for veterinary uses, e.g., for the treatment of live stock or domestic animals, e.g., dogs.

Methods of introduction may also be provided by rechargeable or biodegradable devices. Various slow release polymeric devices have been developed and tested *in vivo* in recent years for the controlled delivery of drugs, including proteinacious biopharmaceuticals. A variety of biocompatible polymers (including hydrogels), including both biodegradable and non-degradable polymers, can be used to form an implant for the sustained release of a hedgehog antagonist at a particular target site.

The preparations of the present invention may be given orally, parenterally, topically, or rectally. They are of course given by forms suitable for each administration route. For example, they are administered in tablets or capsule form, by injection, inhalation, eye lotion, ointment, suppository, etc. administration by injection, infusion or inhalation; topical by lotion or ointment; and rectal by suppositories. Oral and topical administrations are preferred.

The phrases "parenteral administration" and "administered parenterally" as used herein means modes of administration other than enteral and topical administration, usually by injection, and includes, without limitation, intravenous, intramuscular, intraarterial, intrathecal, intracapsular, intraorbital, intracardiac, intradermal, intraperitoneal, transtracheal, subcutaneous, subcuticular, intraarticulare, subcapsular, subarachnoid, intraspinal and intrasternal injection and infusion.

The phrases "systemic administration," "administered systemically," "peripheral administration" and "administered peripherally" as used herein mean the administration of a compound, drug or other material other than directly into the central nervous system, such that it enters the patient's system and, thus, is subject to metabolism and other like processes, for example, subcutaneous administration.

These compounds may be administered to humans and other animals for therapy by any suitable route of administration, including orally, nasally, as by, for example, a spray, rectally, intravaginally, parenterally, intracisternally and topically, as by powders, ointments or drops, including buccally and sublingually.

Regardless of the route of administration selected, the compounds of the present invention, which may be used in a suitable hydrated form, and/or the pharmaceutical

compositions of the present invention, are formulated into pharmaceutically-acceptable dosage forms such as described below or by other conventional methods known to those of skill in the art.

Actual dosage levels of the active ingredients in the pharmaceutical compositions of this invention may be varied so as to obtain an amount of the active ingredient which is effective to achieve the desired therapeutic response for a particular patient, composition, and mode of administration, without being toxic to the patient.

The selected dosage level will depend upon a variety of factors including the activity of the particular compound of the present invention employed, or the ester, salt or amide thereof, the route of administration, the time of administration, the rate of excretion of the particular compound being employed, the duration of the treatment, other drugs, compounds and/or materials used in combination with the particular hedgehog antagonist employed, the age, sex, weight, condition, general health and prior medical history of the patient being treated, and like factors well known in the medical arts.

A physician or veterinarian having ordinary skill in the art can readily determine and prescribe the effective amount of the pharmaceutical composition required. For example, the physician or veterinarian could start doses of the compounds of the invention employed in the pharmaceutical composition at levels lower than that required in order to achieve the desired therapeutic effect and gradually increase the dosage until the desired effect is achieved.

In general, a suitable daily dose of a compound of the invention will be that amount of the compound which is the lowest dose effective to produce a therapeutic effect. Such an effective dose will generally depend upon the factors described above. Generally, intravenous, intracerebroventricular and subcutaneous doses of the compounds of this invention for a patient will range from about 0.0001 to about 100 mg per kilogram of body weight per day.

If desired, the effective daily dose of the active compound may be administered as two, three, four, five, six or more sub-doses administered separately at appropriate intervals throughout the day, optionally, in unit dosage forms.

The term "treatment" is intended to encompass also prophylaxis, therapy and cure.

The patient receiving this treatment is any animal in need, including primates, in particular humans, and other mammals such as equines, cattle, swine and sheep; and poultry and pets in general.

The compound of the invention can be administered as such or in admixtures with pharmaceutically acceptable carriers and can also be administered in conjunction with other antimicrobial agents such as penicillins, cephalosporins, aminoglycosides and glycopeptides. Conjunctive therapy, thus includes sequential, simultaneous and separate administration of the active compound in a way that the therapeutical effects of the first administered one is not entirely disappeared when the subsequent is administered.

V. Pharmaceutical Compositions

While it is possible for a compound of the present invention to be administered alone, it is preferable to administer the compound as a pharmaceutical formulation (composition). The hedgehog antagonists according to the invention may be formulated for administration in any convenient way for use in human or veterinary medicine.

Thus, another aspect of the present invention provides pharmaceutically acceptable compositions comprising a therapeutically-effective amount of one or more of the compounds described above, formulated together with one or more pharmaceutically acceptable carriers (additives) and/or diluents. As described in detail below, the pharmaceutical compositions of the present invention may be specially formulated for administration in solid or liquid form, including those adapted for the following: (1) oral administration, for example, drenches (aqueous or non-aqueous solutions or suspensions), tablets, boluses, powders, granules, pastes for application to the tongue; (2) parenteral administration, for example, by subcutaneous, intramuscular or intravenous injection as, for example, a sterile solution or suspension; (3) topical application, for example, as a cream, ointment or spray applied to the skin; or (4) intravaginally or intrarectally, for example, as a pessary, cream or foam. However, in certain embodiments the subject compounds may be simply dissolved or suspended in sterile water.

The phrase "therapeutically-effective amount" as used herein means that amount of a compound, material, or composition comprising a compound of the present invention which is effective for producing some desired therapeutic effect by inhibiting a hedgehog signaling pathway in at least a sub-population of cells in an animal and thereby blocking the biological consequences of that pathway in the treated cells, at a reasonable benefit/risk ratio applicable to any medical treatment.

The phrase "pharmaceutically acceptable" is employed herein to refer to those compounds, materials, compositions, and/or dosage forms which are, within the scope of sound medical judgment, suitable for use in contact with the tissues of human beings and

animals without excessive toxicity, irritation, allergic response, or other problem or complication, commensurate with a reasonable benefit/risk ratio.

The phrase "pharmaceutically-acceptable carrier" as used herein means a pharmaceutically-acceptable material, composition or vehicle, such as a liquid or solid filler, diluent, excipient, solvent or encapsulating material, involved in carrying or transporting the subject antagonists from one organ, or portion of the body, to another organ, or portion of the body. Each carrier must be "acceptable" in the sense of being compatible with the other ingredients of the formulation and not injurious to the patient. Some examples of materials which can serve as pharmaceutically-acceptable carriers include: (1) sugars, such as lactose, glucose and sucrose; (2) starches, such as corn starch and potato starch; (3) cellulose, and its derivatives, such as sodium carboxymethyl cellulose, ethyl cellulose and cellulose acetate; (4) powdered tragacanth; (5) malt; (6) gelatin; (7) talc; (8) excipients, such as cocoa butter and suppository waxes; (9) oils, such as peanut oil, cottonseed oil, safflower oil, sesame oil, olive oil, corn oil and soybean oil; (10) glycols, such as propylene glycol; (11) polyols, such as glycerin, sorbitol, mannitol and polyethylene glycol; (12) esters, such as ethyl oleate and ethyl laurate; (13) agar; (14) buffering agents, such as magnesium hydroxide and aluminum hydroxide; (15) alginic acid; (16) pyrogen-free water; (17) isotonic saline; (18) Ringer's solution; (19) ethyl alcohol; (20) phosphate buffer solutions; and (21) other non-toxic compatible substances employed in pharmaceutical formulations.

As set out above, certain embodiments of the present hedgehog antagonists may contain a basic functional group, such as amino or alkylamino, and are, thus, capable of forming pharmaceutically-acceptable salts with pharmaceutically-acceptable acids. The term "pharmaceutically-acceptable salts" in this respect, refers to the relatively non-toxic, inorganic and organic acid addition salts of compounds of the present invention. These salts can be prepared *in situ* during the final isolation and purification of the compounds of the invention, or by separately reacting a purified compound of the invention in its free base form with a suitable organic or inorganic acid, and isolating the salt thus formed. Representative salts include the hydrobromide, hydrochloride, sulfate, bisulfate, phosphate, nitrate, acetate, valerate, oleate, palmitate, stearate, laurate, benzoate, lactate, phosphate, tosylate, citrate, maleate, fumarate, succinate, tartrate, napthylate, mesylate, glucoheptonate, lactobionate, and laurylsulphonate salts and the like. (See, for example, Berge et al. (1977) "Pharmaceutical Salts", *J. Pharm. Sci.* 66:1-19)

The pharmaceutically acceptable salts of the subject compounds include the conventional nontoxic salts or quaternary ammonium salts of the compounds, e.g., from non-toxic organic or inorganic acids. For example, such conventional nontoxic salts

include those derived from inorganic acids such as hydrochloride, hydrobromic, sulfuric, sulfamic, phosphoric, nitric, and the like; and the salts prepared from organic acids such as acetic, propionic, succinic, glycolic, stearic, lactic, malic, tartaric, citric, ascorbic, palmitic, maleic, hydroxymaleic, phenylacetic, glutamic, benzoic, salicyclic, sulfanilic, 2-acetoxybenzoic, fumaric, toluenesulfonic, methanesulfonic, ethane disulfonic, oxalic, isothionic, and the like.

In other cases, the compounds of the present invention may contain one or more acidic functional groups and, thus, are capable of forming pharmaceutically-acceptable salts with pharmaceutically-acceptable bases. The term "pharmaceutically-acceptable salts" in these instances refers to the relatively non-toxic, inorganic and organic base addition salts of compounds of the present invention. These salts can likewise be prepared *in situ* during the final isolation and purification of the compounds, or by separately reacting the purified compound in its free acid form with a suitable base, such as the hydroxide, carbonate or bicarbonate of a pharmaceutically-acceptable metal cation, with ammonia, or with a pharmaceutically-acceptable organic primary, secondary or tertiary amine. Representative alkali or alkaline earth salts include the lithium, sodium, potassium, calcium, magnesium, and aluminum salts and the like. Representative organic amines useful for the formation of base addition salts include ethylamine, diethylamine, ethylenediamine, ethanolamine, diethanolamine, piperazine and the like. (See, for example, Berge et al., *supra*)

Wetting agents, emulsifiers and lubricants, such as sodium lauryl sulfate and magnesium stearate, as well as coloring agents, release agents, coating agents, sweetening, flavoring and perfuming agents, preservatives and antioxidants can also be present in the compositions.

Examples of pharmaceutically-acceptable antioxidants include: (1) water soluble antioxidants, such as ascorbic acid, cysteine hydrochloride, sodium bisulfate, sodium metabisulfite, sodium sulfite and the like; (2) oil-soluble antioxidants, such as ascorbyl palmitate, butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), lecithin, propyl gallate, alpha-tocopherol, and the like; and (3) metal chelating agents, such as citric acid, ethylenediamine tetraacetic acid (EDTA), sorbitol, tartaric acid, phosphoric acid, and the like.

Formulations of the present invention include those suitable for oral, nasal, topical (including buccal and sublingual), rectal, vaginal and/or parenteral administration. The formulations may conveniently be presented in unit dosage form and may be prepared by any methods well known in the art of pharmacy. The amount of active ingredient which can be combined with a carrier material to produce a single dosage form will vary

depending upon the host being treated, the particular mode of administration. The amount of active ingredient which can be combined with a carrier material to produce a single dosage form will generally be that amount of the compound which produces a therapeutic effect. Generally, out of one hundred per cent, this amount will range from about 1 per cent to about ninety-nine percent of active ingredient, preferably from about 5 per cent to about 70 per cent, most preferably from about 10 per cent to about 30 per cent.

Methods of preparing these formulations or compositions include the step of bringing into association a compound of the present invention with the carrier and, optionally, one or more accessory ingredients. In general, the formulations are prepared by uniformly and intimately bringing into association a compound of the present invention with liquid carriers, or finely divided solid carriers, or both, and then, if necessary, shaping the product.

Formulations of the invention suitable for oral administration may be in the form of capsules, cachets, pills, tablets, lozenges (using a flavored basis, usually sucrose and acacia or tragacanth), powders, granules, or as a solution or a suspension in an aqueous or non-aqueous liquid, or as an oil-in-water or water-in-oil liquid emulsion, or as an elixir or syrup, or as pastilles (using an inert base, such as gelatin and glycerin, or sucrose and acacia) and/or as mouth washes and the like, each containing a predetermined amount of a compound of the present invention as an active ingredient. A compound of the present invention may also be administered as a bolus, electuary or paste.

In solid dosage forms of the invention for oral administration (capsules, tablets, pills, dragees, powders, granules and the like), the active ingredient is mixed with one or more pharmaceutically-acceptable carriers, such as sodium citrate or dicalcium phosphate, and/or any of the following: (1) fillers or extenders, such as starches, lactose, sucrose, glucose, mannitol, and/or silicic acid; (2) binders, such as, for example, carboxymethylcellulose, alginates, gelatin, polyvinyl pyrrolidone, sucrose and/or acacia; (3) humectants, such as glycerol; (4) disintegrating agents, such as agar-agar, calcium carbonate, potato or tapioca starch, alginic acid, certain silicates, and sodium carbonate; (5) solution retarding agents, such as paraffin; (6) absorption accelerators, such as quaternary ammonium compounds; (7) wetting agents, such as, for example, cetyl alcohol and glycerol monostearate; (8) absorbents, such as kaolin and bentonite clay; (9) lubricants, such a talc, calcium stearate, magnesium stearate, solid polyethylene glycols, sodium lauryl sulfate, and mixtures thereof; and (10) coloring agents. In the case of capsules, tablets and pills, the pharmaceutical compositions may also comprise buffering agents. Solid compositions of a similar type may also be employed as fillers in soft and

hard-filled gelatin capsules using such excipients as lactose or milk sugars, as well as high molecular weight polyethylene glycols and the like.

A tablet may be made by compression or molding, optionally with one or more accessory ingredients. Compressed tablets may be prepared using binder (for example, gelatin or hydroxypropylmethyl cellulose), lubricant, inert diluent, preservative, disintegrant (for example, sodium starch glycolate or cross-linked sodium carboxymethyl cellulose), surface-active or dispersing agent. Molded tablets may be made by molding in a suitable machine a mixture of the powdered compound moistened with an inert liquid diluent.

The tablets, and other solid dosage forms of the pharmaceutical compositions of the present invention, such as dragees, capsules, pills and granules, may optionally be scored or prepared with coatings and shells, such as enteric coatings and other coatings well known in the pharmaceutical-formulating art. They may also be formulated so as to provide slow or controlled release of the active ingredient therein using, for example, hydroxypropylmethyl cellulose in varying proportions to provide the desired release profile, other polymer matrices, liposomes and/or microspheres. They may be sterilized by, for example, filtration through a bacteria-retaining filter, or by incorporating sterilizing agents in the form of sterile solid compositions which can be dissolved in sterile water, or some other sterile injectable medium immediately before use. These compositions may also optionally contain opacifying agents and may be of a composition that they release the active ingredient(s) only, or preferentially, in a certain portion of the gastrointestinal tract, optionally, in a delayed manner. Examples of embedding compositions which can be used include polymeric substances and waxes. The active ingredient can also be in micro-encapsulated form, if appropriate, with one or more of the above-described excipients.

Liquid dosage forms for oral administration of the compounds of the invention include pharmaceutically acceptable emulsions, microemulsions, solutions, suspensions, syrups and elixirs. In addition to the active ingredient, the liquid dosage forms may contain inert diluents commonly used in the art, such as, for example, water or other solvents, solubilizing agents and emulsifiers, such as ethyl alcohol, isopropyl alcohol, ethyl carbonate, ethyl acetate, benzyl alcohol, benzyl benzoate, propylene glycol, 1,3-butylene glycol, oils (in particular, cottonseed, groundnut, corn, germ, olive, castor and sesame oils), glycerol, tetrahydrofuryl alcohol, polyethylene glycols and fatty acid esters of sorbitan, and mixtures thereof.

Besides inert diluents, the oral compositions can also include adjuvants such as wetting agents, emulsifying and suspending agents, sweetening, flavoring, coloring, perfuming and preservative agents.

Suspensions, in addition to the active compounds, may contain suspending agents as, for example, ethoxylated isostearyl alcohols, polyoxyethylene sorbitol and sorbitan esters, microcrystalline cellulose, aluminum metahydroxide, bentonite, agar-agar and tragacanth, and mixtures thereof.

It is known that sterols, such as cholesterol, will form complexes with cyclodextrins. Thus, in preferred embodiments, where the inhibitor is a steroidal alkaloid, it may be formulated with cyclodextrins, such as α-, β- and γ-cyclodextrin, dimethyl- β cyclodextrin and 2-hydroxypropyl-β-cyclodextrin.

Formulations of the pharmaceutical compositions of the invention for rectal or vaginal administration may be presented as a suppository, which may be prepared by mixing one or more compounds of the invention with one or more suitable nonirritating excipients or carriers comprising, for example, cocoa butter, polyethylene glycol, a suppository wax or a salicylate, and which is solid at room temperature, but liquid at body temperature and, therefore, will melt in the rectum or vaginal cavity and release the active hedgehog antagonist.

Formulations of the present invention which are suitable for vaginal administration also include pessaries, tampons, creams, gels, pastes, foams or spray formulations containing such carriers as are known in the art to be appropriate.

Dosage forms for the topical or transdermal administration of a compound of this invention include powders, sprays, ointments, pastes, creams, lotions, gels, solutions, patches and inhalants. The active compound may be mixed under sterile conditions with a pharmaceutically-acceptable carrier, and with any preservatives, buffers, or propellants which may be required.

The ointments, pastes, creams and gels may contain, in addition to an active compound of this invention, excipients, such as animal and vegetable fats, oils, waxes, paraffins, starch, tragacanth, cellulose derivatives, polyethylene glycols, silicones, bentonites, silicic acid, talc and zinc oxide, or mixtures thereof.

Powders and sprays can contain, in addition to a compound of this invention, excipients such as lactose, talc, silicic acid, aluminum hydroxide, calcium silicates and polyamide powder, or mixtures of these substances. Sprays can additionally contain customary propellants, such as chlorofluorohydrocarbons and volatile unsubstituted hydrocarbons, such as butane and propane.

Transdermal patches have the added advantage of providing controlled delivery of a compound of the present invention to the body. Such dosage forms can be made by dissolving or dispersing the hedgehog antagonists in the proper medium. Absorption enhancers can also be used to increase the flux of the hedgehog antagonists across the skin. The rate of such flux can be controlled by either providing a rate controlling membrane or dispersing the compound in a polymer matrix or gel.

Ophthalmic formulations, eye ointments, powders, solutions and the like, are also contemplated as being within the scope of this invention.

Pharmaceutical compositions of this invention suitable for parenteral administration comprise one or more compounds of the invention in combination with one or more pharmaceutically-acceptable sterile isotonic aqueous or nonaqueous solutions, dispersions, suspensions or emulsions, or sterile powders which may be reconstituted into sterile injectable solutions or dispersions just prior to use, which may contain antioxidants, buffers, bacteriostats, solutes which render the formulation isotonic with the blood of the intended recipient or suspending or thickening agents.

Examples of suitable aqueous and nonaqueous carriers which may be employed in the pharmaceutical compositions of the invention include water, ethanol, polyols (such as glycerol, propylene glycol, polyethylene glycol, and the like), and suitable mixtures thereof, vegetable oils, such as olive oil, and injectable organic esters, such as ethyl oleate. Proper fluidity can be maintained, for example, by the use of coating materials, such as lecithin, by the maintenance of the required particle size in the case of dispersions, and by the use of surfactants.

These compositions may also contain adjuvants such as preservatives, wetting agents, emulsifying agents and dispersing agents. Prevention of the action of microorganisms may be ensured by the inclusion of various antibacterial and antifungal agents, for example, paraben, chlorobutanol, phenol sorbic acid, and the like. It may also be desirable to include isotonic agents, such as sugars, sodium chloride, and the like into the compositions. In addition, prolonged absorption of the injectable pharmaceutical form may be brought about by the inclusion of agents which delay absorption such as aluminum monostearate and gelatin.

In some cases, in order to prolong the effect of a drug, it is desirable to slow the absorption of the drug from subcutaneous or intramuscular injection. This may be accomplished by the use of a liquid suspension of crystalline or amorphous material having poor water solubility. The rate of absorption of the drug then depends upon its rate of dissolution which, in turn, may depend upon crystal size and crystalline form.

Alternatively, delayed absorption of a parenterally-administered drug form is accomplished by dissolving or suspending the drug in an oil vehicle.

Injectable depot forms are made by forming microencapsule matrices of the subject compounds in biodegradable polymers such as polylactide-polyglycolide. Depending on the ratio of drug to polymer, and the nature of the particular polymer employed, the rate of drug release can be controlled. Examples of other biodegradable polymers include poly(orthoesters) and poly(anhydrides). Depot injectable formulations are also prepared by entrapping the drug in liposomes or microemulsions which are compatible with body tissue.

When the compounds of the present invention are administered as pharmaceuticals, to humans and animals, they can be given per se or as a pharmaceutical composition containing, for example, 0.1 to 99.5% (more preferably, 0.5 to 90%) of active ingredient in combination with a pharmaceutically acceptable carrier.

The addition of the active compound of the invention to animal feed is preferably accomplished by preparing an appropriate feed premix containing the active compound in an effective amount and incorporating the premix into the complete ration.

Alternatively, an intermediate concentrate or feed supplement containing the active ingredient can be blended into the feed. The way in which such feed premixes and complete rations can be prepared and administered are described in reference books (such as "Applied Animal Nutrition", W.H. Freedman and CO., San Francisco, U.S.A., 1969 or "Livestock Feeds and Feeding" O and B books, Corvallis, Ore., U.S.A., 1977).

VI. Synthetic Schemes and Identification of Active Antagonists

The subjects steroidal alkaloids, and congeners thereof, can be prepared readily by employing the cross-coupling technologies of Suzuki, Stille, and the like. These coupling reactions are carried out under relatively mild conditions and tolerate a wide range of "spectator" functionality.

a. Combinatorial Libraries

The compounds of the present invention, particularly libraries of variants having various representative classes of substituents, are amenable to combinatorial chemistry and other parallel synthesis schemes (see, for example, PCT WO 94/08051). The result is that large libraries of related compounds, e.g. a variegated library of compounds represented above, can be screened rapidly in high throughput assays in order to identify potential hedgehog antagonists lead compounds, as well as to refine the specificity, toxicity, and/or

cytotoxic-kinetic profile of a lead compound. For instance, hedgehog bioactivity assays as described above can be used to screen a library of the subject compounds for those having antagonist activity toward all or a particular hedgehog isoform or activity.

Simply for illustration, a combinatorial library for the purposes of the present invention is a mixture of chemically related compounds which may be screened together for a desired property. The preparation of many related compounds in a single reaction greatly reduces and simplifies the number of screening processes which need to be carried out. Screening for the appropriate physical properties can be done by conventional methods.

Diversity in the library can be created at a variety of different levels. For instance, the substrate aryl groups used in the combinatorial reactions can be diverse in terms of the core aryl moiety, e.g., a variegation in terms of the ring structure, and/or can be varied with respect to the other substituents.

A variety of techniques are available in the art for generating combinatorial libraries of small organic molecules such as the subject hedgehog antagonists. See, for example, Blondelle et al. (1995) Trends Anal. Chem. 14:83; the Affymax U.S. Patents 5,359,115 and 5,362,899: the Ellman U.S. Patent 5,288,514: the Still et al. PCT publication WO 94/08051; Chen et al. (1994) JACS 116:2661: Kerr et al. (1993) JACS 115:252; PCT publications WO92/10092, WO93/09668 and WO91/07087; and the Lerner et al. PCT publication WO93/20242). Accordingly, a variety of libraries on the order of about 100 to 1,000,000 or more diversomers of the subject hedgehog antagonists can be synthesized and screened for particular activity or property.

In an exemplary embodiment, a library of candidate hedgehog antagonists diversomers can be synthesized utilizing a scheme adapted to the techniques described in the Still et al. PCT publication WO 94/08051, e.g., being linked to a polymer bead by a hydrolyzable or photolyzable group e.g., located at one of the positions of the candidate antagonists or a substituent of a synthetic intermediate. According to the Still et al. technique, the library is synthesized on a set of beads, each bead including a set of tags identifying the particular diversomer on that bead. The bead library can then be "plated" on a lawn of hedgehog-sensitive cells for which an inhibitor is sought. The diversomers can be released from the bead, e.g. by hydrolysis. Beads surrounded by areas of no, or diminished, hedgehog sensitivity (e.g., to exogeneously added hedgehog protein), e.g. a "halo", can be selected, and their tags can be "read" to establish the identity of the particular diversomer.

b. Screening Assays

There are a variety of assays availble for determining the ability of a compound to inhibit hedgehog-mediated signaling, many of which can be disposed in high throughput formats. In many drug screening programs which test libraries of compounds and natural extracts, high throughput assays are desirable in order to maximize the number of compounds surveyed in a given period of time. Thus, libraries of synthetic and natural products can be sampled for other steroidal and non-steroidal compounds which have similar activity to jervine with respect inhibition of hedgehog signals.

The availability of purified and recombinant *hedgehog* polypeptides facilitates the generation of assay systems which can be used to screen for drugs, such as small organic molecules, which are antagonists of the normal cellular function of a *hedgehog*, particularly its role in the pathogenesis of cell proliferation and/or differentiation. In one embodiment, the assay evaluates the ability of a compound to modulate binding between a *hedgehog* polypeptide and a *hedgehog* receptor such as *patched*. In other embodiments, the assay merely scores for the ability of a test compound to alter hedgehog-mediated signal transduction. In this manner, a variety of antagonists can be identified. A variety of assay formats will suffice and, in light of the present disclosure, will be comprehended by skilled artisan.

Assays which are performed in cell-free systems, such as may be derived with purified or semi-purified proteins, are often preferred as "primary" screens in that they can be generated to permit rapid development and relatively easy detection of an alteration in a molecular target which is mediated by a test compound. Moreover, the effects of cellular toxicity and/or bioavailability of the test compound can be generally ignored in the *in vitro* system, the assay instead being focused primarily on the effect of the drug on the molecular target as may be manifest in an alteration of binding affinity with receptor proteins.

While not wishing to be bound by any particular theory, should jervine and other steroidal alkaloids exert their activity in the hedgehog signal pathway by interfering with cholesterol-derived hedgehog, e.g., through interaction with the sterol sensing domain of patched (see, e.g., Loftus et al. (1997) *Science* 277:232), an exemplary screening assay for a hedgehog antagonist comprises contacting a compound of interest with a mixture including a *hedgehog* receptor protein (e.g., a cell expressing the *patched* receptor) and a hedgehog protein under conditions in which the receptor is ordinarily capable of binding the *hedgehog* protein, or at least jervine. To the mixture is then added a composition containing a test compound. Detection and quantification of receptor/*hedgehog* and/or receptor/jervine complexes provides a means for determining the test compound's efficacy

at inhibiting (or potentiating) complex formation between the receptor protein and the *hedgehog* polypeptide or the jervine antagonist. The efficacy of the compound can be assessed by generating dose response curves from data obtained using various concentrations of the test compound, and by comparing the results to that obtained with jervine Moreover, a control assay can also be performed to provide a baseline for comparison. In the control assay, isolated and purified *hedgehog* polypeptide is added to the receptor protein, and the formation of receptor/*hedgehog* complex is quantitated in the absence of the test compound.

In an illustrative embodiment, the polypeptide utilized as a *hedgehog* receptor can be generated from the *patched* protein, and in particular, includes the steroid sensing domain, e.g., and a soluble portion of the protein including a functional steroid sensing domain. Accordingly, an exemplary screening assay includes all or a suitable portion of the *patched* protein which can be obtained from, for example, the human *patched* gene (GenBank U43148) or other vertebrate sources (see GenBank Accession numbers U40074 for chicken *patched* and U46155 for mouse *patched*), as well as from drosophila (GenBank Accession number M28999) or other invertebrate sources. The *patched* protein can be provided in the screening assay as a whole protein (preferably expressed on the surface of a cell), or alternatively as a fragment of the full length protein, e.g., which includes the steroid sensing domain and/or at least a portion which binds to *hedgehog* polypeptides, e.g., as one or both of the substantial extracellular domains (e.g. corresponding to residues Asn120-Ser438 and/or Arg770-Trp1027 of the human *patched* protein. For instance, the *patched* protein can be provided in soluble form, as for example a preparation of one of the extracellular domains, or a preparation of both of the extracellular domains which are covalently connected by an unstructured linker (see, for example, Huston et al. (1988) PNAS 85:4879; and U.S. Patent No. 5,091,513). In other embodiments, the protein can be provided as part of a liposomal preparation or expressed on the surface of a cell. The *patched* protein can derived from a recombinant gene, e.g., being ectopically expressed in a heterologous cell. For instance, the protein can be expressed on oocytes, mammalian cells (e.g., COS, CHO, 3T3 or the like), or yeast cell by standard recombinant DNA techniques. These recombinant cells can be used for receptor binding, signal transduction or gene expression assays. Stone et al. (1996) Nature 384:129-34; and Marigo et al. (1996) Nature 384:176-9 illustrate binding assays of human *hedgehog* to patched, such as a chicken *patched* protein ectopically expressed in *Xenopus laevis* oocytes. The assay system of Marigo et al., for example, can be adapted to the present drug screening assays. As illustrated in that reference, *Shh* binds to the *patched* protein in a selective, saturable, dose-dependent manner, thus demonstrating that *patched* is a receptor for *Shh*.

Complex formation between the *hedgehog* polypeptide or jervine and a *hedgehog* receptor may be detected by a variety of techniques. For instance, modulation of the formation of complexes can be quantitated using, for example, detectably labelled proteins such as radiolabelled, fluorescently labelled, or enzymatically labelled *hedgehog* polypeptides, by immunoassay, or by chromatographic detection.

Typically, for cell-free assays, it will be desirable to immobilize either the *hedgehog* receptor or the *hedgehog* polypeptide or jervine molecule to facilitate separation of receptor complexes from uncomplexed forms of one of the protein, as well as to accommodate automation of the assay. In one embodiment, a fusion protein can be provided which adds a domain that allows the protein to be bound to a matrix. For example, glutathione-S-transferase/receptor (GST/receptor) fusion proteins can be adsorbed onto glutathione sepharose beads (Sigma Chemical, St. Louis, MO) or glutathione derivatized microtitre plates, which are then combined with jervine or the *hedgehog* polypeptide, e.g. an ^{35}S-labeled *hedgehog* polypeptide, and the test compound and incubated under conditions conducive to complex formation, e.g. at physiological conditions for salt and pH, though slightly more stringent conditions may be desired. Following incubation, the beads are washed to remove any unbound ligand, and the matrix bead-bound radiolabel determined directly (e.g. beads placed in scintillant), or in the supernatant after the complexes are dissociated. Alternatively, the complexes can be dissociated from the bead, separated by SDS-PAGE gel, and the level of *hedgehog* polypeptide or jervine found in the bead fraction quantitated from the gel using standard techniques (HPLC, gel electrophoresis, etc).

Where the desired portion of the *hedgehog* receptor (or other *hedgehog* binding molecule) cannot be provided in soluble form, liposomal vesicles can be used to provide manipulatable and isolatable sources of the receptor. For example, both authentic and recombinant forms of the *patched* protein can be reconstituted in artificial lipid vesicles (e.g. phosphatidylcholine liposomes) or in cell membrane-derived vesicles (see, for example, Bear et al. (1992) Cell 68:809-818; Newton et al. (1983) Biochemistry 22:6110-6117; and Reber et al. (1987) J Biol Chem 262:11369-11374).

In addition to cell-free assays, such as described above, the compounds of the subject invention can also be tested in cell-based assays. In one embodiment, cell which are sensitive to *hedgehog* induction, e.g. *patched*-expressing cells or other cells sensitive to *hedgehog* induction, can be contacted with a *hedgehog* protein and a test agent of interest, with the assay scoring for anything from simple binding to the cell to inhibition in *hedgehog* inductive responses by the target cell in the presence and absence of the test agent.

In addition to characterizing cells that naturally express the *patched* protein, cells which have been genetically engineered to ectopically express *patched* can be utilized for drug screening assays. As an example, cells which either express low levels or lack expression of the *patched* protein, e.g. *Xenopus laevis* oocytes, COS cells or yeast cells, can be genetically modified using standard techniques to ectopically express the *patched* protein. (see Marigo et al., *supra*).

The resulting recombinant cells, e.g., which express a functional *patched* receptor, can be utilized in receptor binding assays to identify agonist or anatagonsts of *hedgehog* binding. Binding assays can be performed using whole cells. Furthermore, the recombinant cells of the present invention can be engineered to include other heterolgous genes encoding proteins involved in *hedgehog*-dependent signal pathways. For example, the gene products of one or more of *smoothened*, *costal-2*, *fused*, and/or *suppressor of fused* can be co-expressed with *patched* in the reagent cell, with assays being sensitive to the functional reconstituion of the *hedgehog* signal transduction cascade.

Alternatively, liposomal preparations using reconstituted *patched* protein can be utilized. *Patched* protein purified from detergent extracts from both authentic and recombinant origins can be reconstituted in in artificial lipid vesicles (e.g. phosphatidylcholine liposomes) or in cell membrane-derived vesicles (see, for example, Bear et al. (1992) Cell 68:809-818; Newton et al. (1983) Biochemistry 22:6110-6117; and Reber et al. (1987) J Biol Chem 262:11369-11374). The lamellar structure and size of the resulting liposomes can be characterized using electron microscopy. External orientation of the *patched* protein in the reconstituted membranes can be demonstrated, for example, by immunoelectron microscopy. The *hedgehog* protein binding activity of liposomes containing *patched* and liposomes without the protein in the presence of candidate agents can be compared in order to identify potential modulators of the *hedgehog-patched* interaction.

The *hedgehog* protein used in these cell-based assays can be provided as a purified source (natural or recombinant in origin), or in the form of cells/tissue which express the protein and which are co-cultured with the target cells, and is preferably a cholesterol-derived form. In addition to binding studies, by detecting changes in intracellular signals, such as alterations in second messengers or gene expression, in *patched*-expressing cells contacted with a test agent, candidate hedgehog antagonists can be identified.

A number of gene products have been implicated in *patched*-mediated signal transduction, including *patched*, the transcription factor *cubitus interruptus* (ci), the serine/threonine kinase *fused* (fu) and the gene products of *costal-2*, *smoothened* and *suppressor of fused*.

The induction of cells by hedgehog proteins sets in motion a cascade involving the activation and inhibition of downstream effectors, the ultimate consequence of which is, in some instances, a detectable change in the transcription or translation of a gene. Potential transcriptional targets of *hedgehog*-mediated signaling are the *patched* gene (Hidalgo and Ingham, 1990 Development 110, 291-301; Marigo et al., 1996) and the vertebrate homologs of the drosophila cubitus interruptus gene, the *GLI* genes (Hui et al. (1994) Dev Biol 162:402-413). *Patched* gene expression has been shown to be induced in cells of the limb bud and the neural plate that are responsive to *Shh*. (Marigo et al. (1996) PNAS 93:9346-51; Marigo et al. (1996) Development 122:1225-1233). The *GLI* genes encode putative transcription factors having zinc finger DNA binding domains (Orenic et al. (1990) Genes & Dev 4:1053-1067; Kinzler et al. (1990) Mol Cell Biol 10:634-642). Transcription of the *GLI* gene has been reported to be upregulated in response to *hedgehog* in limb buds, while transcription of the *GLI3* gene is downregulated in response to *hedgehog* induction (Marigo et al. (1996) Development 122:1225-1233). By selecting transcriptional regulatory sequences from such target genes, e.g. from *patched* or *GLI* genes, that are responsible for the up- or down regulation of these genes in response to *hedgehog* signaling, and operatively linking such promoters to a reporter gene, one can derive a transcription based assay which is sensitive to the ability of a specific test compound to modify *hedgehog*-mediated signaling pathways. Expression of the reporter gene, thus, provides a valuable screening tool for the development of compounds that act as antagonists of *hedgehog*.

Reporter gene based assays of this invention measure the end stage of the above described cascade of events, e.g., transcriptional modulation. Accordingly, in practicing one embodiment of the assay, a reporter gene construct is inserted into the reagent cell in order to generate a detection signal dependent on *hedgehog* signaling. To identify potential regulatory elements responsive to *hedgehog* signaling present in the transcriptional regulatory sequence of a target gene, nested deletions of genomic clones of the target gene can be constructed using standard techniques. See, for example, Current Protocols in Molecular Biology, Ausubel, F.M. et al. (eds.) Greene Publishing Associates, (1989); U.S. Patent 5,266,488; Sato et al. (1995) J Biol Chem 270:10314-10322; and Kube et al. (1995) Cytokine 7:1-7. A nested set of DNA fragments from the gene's 5'-flanking region are placed upstream of a reporter gene, such as the luciferase gene, and assayed for their ability to direct reporter gene expression in *patched* expressing cells. Host cells transiently transfected with reporter gene constructs can be scored for the regulation of expression of the reporter gene in the presence and absence of *hedgehog* to determine regulatory sequences which are responsive to *patched*-dependent signaling.

In practicing one embodiment of the assay, a reporter gene construct is inserted into the reagent cell in order to generate a detection signal dependent on second messengers generated by induction with *hedgehog* protein. Typically, the reporter gene construct will include a reporter gene in operative linkage with one or more transcriptional regulatory elements responsive to the *hedgehog* activity, with the level of expression of the reporter gene providing the *hedgehog*-dependent detection signal. The amount of transcription from the reporter gene may be measured using any method known to those of skill in the art to be suitable. For example, mRNA expression from the reporter gene may be detected using RNAse protection or RNA-based PCR, or the protein product of the reporter gene may be identified by a characteristic stain or an intrinsic activity. The amount of expression from the reporter gene is then compared to the amount of expression in either the same cell in the absence of the test compound (or *hedgehog*) or it may be compared with the amount of transcription in a substantially identical cell that lacks the target receptor protein. Any statistically or otherwise significant difference in the amount of transcription indicates that the test compound has in some manner altered the signal transduction activity of the *hedgehog* protein, e.g., the test compound is a potential hedgehog antagonist.

As described in further detail below, in preferred embodiments the gene product of the reporter is detected by an intrinsic activity associated with that product. For instance, the reporter gene may encode a gene product that, by enzymatic activity, gives rise to a detection signal based on color, fluorescence, or luminescence. In other preferred embodiments, the reporter or marker gene provides a selective growth advantage, e.g., the reporter gene may enhance cell viability, relieve a cell nutritional requirement, and/or provide resistance to a drug.

Preferred reporter genes are those that are readily detectable. The reporter gene may also be included in the construct in the form of a fusion gene with a gene that includes desired transcriptional regulatory sequences or exhibits other desirable properties. Examples of reporter genes include, but are not limited to CAT (chloramphenicol acetyl transferase) (Alton and Vapnek (1979), Nature 282: 864-869) luciferase, and other enzyme detection systems, such as beta-galactosidase; firefly luciferase (deWet et al. (1987), Mol. Cell. Biol. 7:725-737); bacterial luciferase (Engebrecht and Silverman (1984), PNAS 1: 4154-4158; Baldwin et al. (1984), Biochemistry 23: 3663-3667); alkaline phosphatase (Toh et al. (1989) Eur. J. Biochem. 182: 231-238, Hall et al. (1983) J. Mol. Appl. Gen. 2: 101), human placental secreted alkaline phosphatase (Cullen and Malim (1992) Methods in Enzymol. 216:362-368).

Transcriptional control elements which may be included in a reporter gene construct include, but are not limited to, promoters, enhancers, and repressor and activator binding sites. Suitable transcriptional regulatory elements may be derived from the transcriptional regulatory regions of genes whose expression is induced after modulation of a *hedgehog* signal transduction pathway. The characteristics of preferred genes from which the transcriptional control elements are derived include, but are not limited to, low or undetectable expression in quiescent cells, rapid induction at the transcriptional level within minutes of extracellular simulation, induction that is transient and independent of new protein synthesis, subsequent shut-off of transcription requires new protein synthesis, and mRNAs transcribed from these genes have a short half-life. It is not necessary for all of these properties to be present.

Moreover, a number of assays are known in the art for detecting inhibitors of cholesterol biosynthesis and can be readily adapted for determining if the subject hedgehog antagonists disrupt cholesterol homeosynthesis, e.g., by inhibiting biosynthesis and/or transport of sterols.

To illustrate, pores formed in the membranes of animal cells by complexes of sterols and the polyene antibiotic amphotericin B can efficiently kill the cells. Thus, in the absence of exogenous sources of cholesterol, inhibitors of enzymes in the cholesterol biosynthetic pathway render cells resistant to amphotericin B. However, in the case of class 2 inhibitors, the increase in cholesterol in the plasma membrane should in fact sensitive the cells to amphotericin B killing. Preincubation of Chinese hamster ovary cells with a test compound which disrupts cholesterol homoeostasis is a manner similar to jervine, such as a test steroidal alkaloid, will sensitize cells to amphotericin B killing. This can be used, therefore, to assay test compounds and is amenable to high through-put screening. A simple two-step protocol in which cells are preincubated (15-24 h) with potential inhibitors and then treated (3-6 h) with amphotericin B is described by Krieger (1983) Anal Biochem 135:383-391, and is a sensitive method for detecting direct (e.g., competitive) and regulatory inhibitors of cholesterol biosynthesis. This protocol may prove useful in detecting potential hedgehog antagonists.

SREBP cleavage-activating protein (SCAP) stimulates the proteolytic cleavage of membrane-bound SREBPs, thereby initiating the release of NH2-terminal fragments from cell membranes. The liberated fragments enter the nucleus and stimulate transcription of genes involved in synthesis and uptake of cholesterol and fatty acids. Sterols repress cleavage of SREBPs, apparently by interacting with the membrane attachment domain of SCAP. In one embodiment, the ability of a test agent to interfere with sterol transport in a manner similar to jervine can be assayed by generation of activated SCAP or SREBP

proteins. For instance, a particularly desirable embodiment, due to its ability to be used in high throughput screening, is a reporter gene based assay which detects SREBP-dependent gene transcription. A variey of genes have been described in the art as including SREBP responsive elements, and which are candidate for generation of reporter gene constructs. For example, Bist et al. (1997) PNAS 94 (20): 10693-8 describes the presence of SREBP responsive elements in the Caveolin gene; Wang et al. (1997) J Biol Chem 272:26367-74 describes such elements in the FAS gene; Magana et al. (1996) J Biol Chem 271:32689-94 describe the presence of SREBP-RE in the fatty-acid synthase gene; and Ericsson et al (1996) PNAS 93:945-50 describe SREBP binding sites in the farnesyl diphosphate synthase gene. Thus, such reporter gene constructs as the FAS promoter-luciferase reporter described by Wang et al. supra, or the squalene synthase promoter-luciferase reporter described by Guan et al. (1997) J Biol Chem 272:10295-302 can be utilized in an assay for detecting potential equivalents to jervine. Briefly, in the absence of a class 2 inhibitor, sterol transport occurs at some level and SREBP-dependent transcription occurs at a certain rate. Inhibition of sterol trafficking by jervine or the like results in an increase in sterol precursors in the plasma membrane and a decrease of such precrusors in the endoplasmic reticulum. The latter causes activation of SCAP-mediated cleavage of SREBP, and a concomitant increase in expression of SREBP-RE reporter gene. Detection of reporter gene expression can be accomplished by any of a wide range of techniques known in the art. For example, the reporter gene may one which confers drug resistance, such as to zeocin or hygromycin. Jervine, or another compound capable of inhibiting cholesterol homeostasis in a similar manner, will cause increased resistance to the drug as expression of the reporter gene is increased.

In still other embodiments, the ability of a test agent to effect the activity of 3-hydroxy-3-methyl-glutaryl coenzyme A (HMG-CoA) reductase can be used to detect compounds which, like jervine, affect cholesterol homeostasis. Conditions of low cholesterol or other sterols in the endoplasmic reticulum, such as caused by class 2 inhibitors like jervine, result in activation of HMG-CoA reductase. This activation can be detected, for instance, by detecting increased expression of HMG-CoA (Chambers et al. (1997) Am J Med Genet 68:322-7) or by detecting increase enzymatic activity, such as in the HMG-CoA reductase reduction of the substrate, [^{14}C]HMG-CoA (see US Patent 5,753,675).

Exemplification

The invention now being generally described, it will be more readily understood by reference to the following examples which are included merely for purposes of illustration

of certain aspects and embodiments of the present invention, and are not intended to limit the invention.

Example 1: Steroidal Alkaloids can disrupt Hedgehog Signaling

In order to demonstrate an effect on Shh signaling, we chose the chick (38) as a more tractable experimental system than the rodents, sheep and other mammals in which teratogen-induced HPE predominantly has been studied (14, 15, 16, 29, 39). Chick embryos are easily cultured and manipulated and, as seen in Fig. 2, exposure of these embryos to jervine at the intermediate to definitive streak state (40) induced external malformations characteristic of HPE (similar results were obtained with cyclopamine; data not shown). The severity of these defects varied among treated embryos, as seen in panels B-E by the degree of loss of midline structures and approximation of paired lateral structures. These midline deficits thus result in the fusion of the mandibular and maxillary processes as well as the optic vesicles and olfactory processes, with consequent cyclopia and formation of a proboscis-like structure consisting of fused nasal chambers in the most severely affected embryos (Fig. 2E).

As seen in Fig. 2 in ovo treatment produced variable defects and some embryos displayed normal morphology, even at the highest concentrations tested (50μM, jervine 5/10 and cyclopamine 2/10, data now shown). The variability of these effects may be due to imprecise embryonic staging and difficulties in applying these hydrophobic compounds uniformly. To reduce this variability and better evaluate the potential effects of teratogenic compounds on *Shh* signaling we established an explant assay that allowed for precise tissue staging and more uniform application of the teratogen (41). As shown in Fig. 3A, medial neural plate with notochord was explanted from a region just rostral to Hensen's node. At this level, the medial neural plte does not yet express floor plate cell (HNF3β) or motor neuron (Isl-l) markers (42, 43, data not shown), although the notochord does express Shh (44, 45, data not shown). As seen in Fig. 3B, after a 40 hour incubation the neutral plate expresses HNF3β and Isl-1. Expression of these markers has been shown to depend upon *Shh* signaling, both in vivo and in vitro (2, 45), and these midline explants thus constitute an integrated assay of *Shh* signaling, comprising both inducing and target tissues.

To determine whether synthetic and plant-derived teratogens block *Shh* signaling we exposed midline explants to varying concentrations of the drugs AY 9944 and triparanol and to the steroidal alkaloids cyclopamine and jervine. As can be seen in Fig. 3D-K, all of these compounds affect *Shh* signaling, with a complete loss of HNF3 and Isl-

l expression consistently caused by sufficiently high concentrations (Fig. 3E,G,J,K). At concentrations several-fold below those required for complete inhibition, all of the teratogenic compounds are able to block HNF3β expression while retaining and often enhancing Isl-1 expression (Fig. 3D,F,H,H). These effects are fully consistent with inhibition of *Shh* signaling (see below). In contract, the structurally related but not teratogenic steroidal alkaloid tomatidine (see Fig. 1, ref. 46, data not shown) is unable to block expression of HNF3β and Isl-1, even at concentrations two orders of magnitude higher than the inhibitory concentrations of jervine and cyclopamine (Fig. 3C).

Inhibitory compounds do not block Shh processing

Because the midline explants contain both inducing and responding tissues, we set out to distinguish possible effects of these inhibitory compounds on signal production versus possible effects on signal response. The Shh protein undergoes an intramolecular processing reaction that involves internal cleavage and gives rise to an amino-terminal product (Shh-Np responsible for all known signaling activities. The first step of the autoprocessing reaction, mediated by the carboxy-terminal sequences within the precursor, entails an internal rearrangement at the site of cleavage to replace the scissile peptide bond by the thioester involving a Cys side chain. In the second step cholesterol supplies the nucleophile (the 3β-OH) that attacks the thioester intermediate, and remains covalently attached as an adduct to Shh-Np (11, 13). Autoprocessing thus is required to release active signal and the cholesterol adduct restricts the tissue distribution of the signal by causing it to associate with the cell surface (12,13).

Given this role of cholesterol in the giogenesis of Hedgehog proteins, an effect of these compounds on Shh-Np production is a particularly appealing possibility since jervine and cyclopamine structurally resemble cholesterol (Fig. 1) and AY 9944 and triparanol inhibit specific late-acting cholesterol biosynthetic enzymes (17, 18, 19, 22). To examine potential effects of these compounds on Shh processing we utilized HK293 cells cultured in lipid-depleted serum and carrying a stable integrated construct for expression of Shh under ecdysone-inducible control (47). Shh protein expression in these cells can be induced by addition of muristerone A, an ecdysone analog. As observed in embryos this protein is efficiently processed (Fig 4A, lanes 1 and 2), with little or no detectable accumulation of precursor (M_r 45 kD). Addition of jervine, cyclopamine, tomatidine, AY 9944, or triparanol during the 24-hour induction period did not diminish Shh-N_p production nor induce accumulation of unprocessed precursor, even at doses 5-fold higher than those required to completely inhibit Shh signaling (Figure 4A, lanes 4-13). All of the amino-terminal cleavage product generated in the presence of these compounds is detected

in cell lysates, not the culture medium (data not shown), and has the same electrophoretic mobility as cholesterol-modified Shh-N_p. These observations are consistent with the presence of a sterol adduct in the amino-terminal cleavage product, since lack of such an adduct is associated with release into the medium and with decreased electrophoretic mobility (the unprocessed amino-terminal fragment is designated Shh-N to distinguish it from processed Shh-Np; see lanes 8,9,17). We also failed to observe any change in efficiency of Shh processing or behavior of Shh-NP in transiently-transfected COS-7 or QT6 CELLS treated with these compounds (48). We also have observed that chick embryos treated with jervine after floor plate induction displayed the normal apical localization of Shh protein within floor plate cells (49).

Because of their structural similarity to cholesterol, we also investigated the potential effects of the plant compounds on an in vitro autoprocessing reaction utilizing purified components. The protein utilized in this reaction is derived by replacement of all but six codons of the *Drosophila Shh* amino-terminal coding region with sequences encoding a hexahistidine purification tag (10). The resulting 29kDa protein, His6Hh-C, in purified form undergoes autoprocessing in a cholesterol-dependent manner to yield a 25kD product (50). As seen in Fig. 5A neither jervine, cyclopamine, nor tomatidine inhibit this cholesterol-stimulated autoprocessing reaction, even at concentrations 27-fold higher than that of cholesterol. Given the presence of 3β-OH in each of the plant compounds (Fig. 1), we also tested their ability to replace cholesterol in providing the nucleophilic group during processing. As seen in Fig. 5B, no appreciable cleavage is stimulated by addition of these compounds in the absence of cholesterol.

The observation that cholesterol synthesis inhibitors such as AY 9944 and triparanol do not inhibit processing raises the possibility that cholesterol biosynthetic precursors, which accumulate in treated cells (see below), may participate in the reaction. Figure 5C shows that the in vitro reaction can be driven by desmosterol, 7-dehydrocholesterol (7DHC), and lathosterol with efficiencies similar to that of cholesterol. Desmosterol and 7DHC are the major precursors reported to accumulate in cells treated with triparanol and AY 9944, respectively. Lanosterl, a 30 carbon cholesterol precursor, on the other hand is unable to participate in the reaction, perhaps due to steric interference by the two methyl groups attached to the C4 carbon near the 3-hydroxyl. In other studies of this in vitro reaction we have observed a requirement for an unhindered hydroxyl at the 3β position on a sterol nucleus, although neither the 8-carbon side chian nor the number or position(s) of the double bond(s) in the sterol nucleus appear to critically affect efficiency (51). These observations suggest that all 27 carbon sterol intermediates in the biosynthetic pathway are potential adducts in the autoprocessing reaction, and may account for the

unimpaired efficiency of processing in the presence of distal synthesis inhibitors. Thus, although the extent of Shh processing in cultured cells and its localization in vivo appears to be unaffected by these inhibitory compounds (Fig. 4), we can not rule out the possibility that the sterol adduct may differ and that such an abnormally modified signal may have distinct biological properties.

Inhibitory compounds specifically affect the response to *Shh* signaling

Since our studies of processing provided n evidence for an inhibitory effect of these compounds on Shh signal production, we examined the alternative possibility that these compound affect response of target tissues. For these studies we utilized an intermediate neural plate explant lacking any endogenous source of inducing signal (41, see Fig. 6A). Recombinant Shh-N protein (45, 52, 53, 54), lacking a sterol adduct, suppresses molecular markers such as Pax7 (55, see Fig. 6B, C), normally expressed in dorsal cell types, and induces ventral markers such as Isl-l and HNF3β (Fig. 6D,E), normally expressed in motor neurons and floor plate cells. These cellular responses are elicited in a concentration-dependent manner, with repression of Pax7 observed at concentrations of Shh-N that are insufficient for induction of HNF38 (ref. 55,2 nM, Fig. 6B,C). Isl-l and HNF3β occurring at the expense of Isl-l (note that the induction of Isl-l at 6.25 nM Shh-N in Fig. 6D is abolished at 25nM in 6E).

The teratogenic compounds are able to block completely the repression of Pax7 (at 2 nM Shh-N; Fig. 6F-I) and the induction of Isl-1 and HNF3β (at 25 nM Shh-N; Fig.6)-S). In addition tomatidine produces partial inhibition, but only at concentrations 100200 fold higher than those required for complete inhibition by jervine and cyclopamine (Fig. 6T). A complete inhibition of the 24 nM response to Shh-N requires does of teratogenic compounds 2-4 higher than those required to completely block the 2 nM response; inhibition of responses to higher concentrations of Shh-N requires higher drug concentrations. Another dose dependent effect can be noted in Fig. 6K-N, where drug concentrations two fold below the thresholds required for complete inhibition of the 25 nM response (induction of HNF3β) result in retention or expansion of Isl-l expression. A similar expansion of Isl-1 at intermediate drug concentrations was seen for midline explants (Fig. 3D-G), indicating that at a fixed level of stimulation by Shh-N, distinct degrees of pathway activation can be produced by distinct inhibitor concentrations.

To further examine the specificity of these compounds we tested their effects on induction of a neural crest-like phenotype by BMP7. The BMP7 signaling protein is expressed in ectodermal cells adjacent to the neural plate, and appears to function in

induction of neural crest and dorsal neural tube cell fates 956). To avoid contamination with endogenous lateral signals, the explants used for these studies were taken from the ventral neural plate, but excluded the notochord and the midline (Fig 7A). Addition of BMP7 protein induced formation of migratory cells that express the HNK-1 surface antigen (compare Figs. 7B,C), features characteristic of neutral crest cells (56). Neither cell migration nor expression HNK-1 were blocked by addition of jervine at 10 μM (Fig. 7D), a concentration exceeding that required for a complete block of Shh-N signaling. Similar results were obtained with tomatidine and with cyclopamine. These compounds also failed to inhibit formation of migratory HNK-1 positive cells from explants containing dorsal neural plate and contiguous epidermal ectoderm (49), which serves as an endogenous source of BMP activity (56).

Drug effects upon cholesterol homeostatis

Pervious reports indicate that triparanol and AY 944 cause the accumulation of cholesterol precursors (predominantly desmosterol and 7-dehycholesterol (7DHC) by specifically inhibiting late-acting enzymes of cholesterol biosynthesis (desmosterol Δ24-reductase and 7DHC Δ7-reductase, respectively, 17, 18, 19, 22), and a preliminary analysis of jervine also revealed an effect upon cholesterol biosynthesis (30). A direct comparison of the effects of these compounds on human primary lymphoblast cultures (57) revealed that all of them, including tomatidine, cause a relative decrease in cholesterol levels and an increase in the levels of other sterols (Table I, ref 58).

Table 1. Teratogenic compounds disrupt cholesterol homeostasis in cultured cells. Cholesterol biosynthesis is inhibited in primary human lymphoblasts cultured in the presence of the teratogenic compounds and tomatidine (58). The sterol profiles (57) from these cultures reveal the accumulation of multiple 27-, 28- and 29-carbon sterol precursors of cholesterol (59, 60). Esterification of PM-labeled [3H]-cholesterol in rat hepatoma cells is also inhibited by all of the compounds (63).

Table 1. Effects of synthetic and plant-derived compounds on cholesterol homeostasis.

A. Cholesterol Biosynthesis Assay

	Control	AY9944 (μM)			Triparanol (μM)			Jervine (μM)			Cyclopamine (μM)			Tomatidine (μM)		
		0.25	0.5	1.0	0.25	0.5	1.0	1.25	2.5	5.0	1.25	2.5	5.0	1.25	2.5	5.0
Total Sterols (μg/mg protein)	9.6	7.6	8.3	8.3	4.1	5.1	3.1	8.8	8.4	10	8.4	8.5	8.3	7.8	7.8	5.6
Percent Sterols																
Cholesterol	95	30	33	34	56	45	51	90	90	88	87	76	68	54	42	32
Non-Cholesterol Sterols																
1. C27 Sterols																
a. Desmosterol	1.9				9.1	8.7	6.7	2.5	2.4	2.7	4.2	7.1	11			
b. 7 Dehydrodesmosterol		3.5	3.0	1.9	6.0	4.1	2.9						0.8	0.8	0.8	0.5
c. Cholesta-7,24-dien-3β-ol		1.8	1.9	1.6	3.1	2.4	2.6		0.5	0.5	0.6	0.9	1.6	0.9	0.9	0.7
d. Zymosterol					8.3	27	23	1.7	2.0	2.3	2.3	4.5	4.7			
e. Cholesta-8(14)-en-3β-ol		9.7	14	20	9.1	8.7	7.3	1.0	1.7	2.3	0.9	2.5	2.7	6.7	8.9	8.7
f. 7 Dehydrocholesterol		50	36	16				1.5	1.4	1.3	2.4	4.2	6.3	19	14	9.8
g. Lathosterol	1.3	6.2	7.3	7.9										4.9	4.7	3.6
h. C27 Sterol 1 (mw 384)				5.3										7.0	13	20
i. C27 Sterol 2 (mw 382)				6.0											4.1	4.7
j. C27 Oxysterol 1 (mw 400)														1.0	2.4	4.5
k. C27 Oxysterol 2 (mw 400)														2.0	5.0	11
2. C28 Sterols	0.7		1.1	2.8	4.4	2.6	1.5	1.2	0.7	0.7	1.2	1.3	1.8			1.6
3. C29 Sterols	1		3.3	4.8	7.8	8.1	5.5	0.8	0.8	1.6	0.7	1.2	3.1			3.1

B. Cholesterol Esterification Assay

Percent Inhibition (Incorporation of label into cholesteryl ester*)	AY9944 (μM)			Triparanol (μM)			Jervine (μM)			Cyclopamine (μM)			Tomatidine (μM)		
	2.5	5.0	10	2.5	5.0	10	2.5	5.0	10	2.5	5.0	10	2.5	5.0	10
^{3}H-Cholesterol	39	56	88	49	57	79	24	44	50	48	67	79	31	33	39
^{14}C-Oleic Acid	20	35	51	54	65	81	28	36	49	45	62	74	30	64	52

* The percent of label taken up that was converted to cholesteryl ester was 6%/ hour for ^{3}H-cholesterol and 3.6%/hour for ^{14}C-oleic acid

The accumulating sterols largely comprise established intermediates in the cholesterol biosynthetic pathway or closely related species that might be generated by action of the giosynthetic enzymes upon these intermediates (59). Tomatidine would appear to be the exception to this general rule, with accumulation to relatively high levels of several unusual sterols (60).

Reduction of cholesterol levels coupled with an accumulation of cholesterol biosynthetic precursors are effects observed for a group of compounds that have been termed class 2 inhibitors of cholesterol biosynthesis (61, 62). These compounds appear to act by inhibiting sterol flux between the plasma membrane (PM) and the endoplasmic reticulum (ER). Since cholesterol biosynthetic enzymes are located in the ER, and sterol precursors of cholesterol are highly concentrated in the PM, such a block in transport results in an overall reduction of cholesterol levels. We measured the effects of the synthetic and plant compounds upon esterification of exogenously added 3H-labelled cholesterol (63), a process which requires transport of PM cholesterol to the ER. We observed inhibition of esterification oat levels ranging for 25-75% for these compounds. An effect of AY 9944 on sterol transport previously has been reported (23), but this is the least active of the compounds we tested in inhibition of esterification. Our data therefore suggest that transport inhibition may be a factor in the effects of all of these compounds on sterol profiles, consistent with the general accumulation of multiple cholesterol biosynthetic precursors. In addition, however, AY 9944 and triparanol cause accumulation to high levels of 7DHC and desmosterol, respectively, consistent with the well-known effects of these compounds on the 7DHC Δ7-reductase and desmosteroal Δ24-reductase enzymes.

Discussion

The teratogenic effects of distal inhibitors of cholesterol biosynthesis have been known and studied for more than thirty years (14, 15). Similarly, cyclopamine and jervine were identified about thirty years ago as the plant compounds responsible for the teratogenic effects of the range plant *Veratrum californicum* (28, 29). The most dramatic teratogenic effect of these compounds is the induction of cyclopia and other features of severe holoprosencephaly (HPE); the recent discovery that HPE is also caused by mutations at the murine and human loci suggested the possibility that these compounds may act to block the *Shh* signaling pathway. Our studies have verified the HPE-inducing properties of these compounds in chick embryos. We have further examined the early

molecular correlates of these teratogenic effects and have demonstrated that these compounds block the induction by Shh protein of ventral cell types in chick neural plate explants.

Despite the inhibitory effects of these teratogens on cholesterol biosynthesis (17, 18, 19, 22, 30, see above), we found that none of the compounds appears to interfere with Shh processing in cultured cells, and that the plant alkaloids neither participate in nor inhibit an in vitro Hh protein autoprocessing reaction utilizing purified components. Instead, it is the response to *Shh* signaling that is affected, as indicated by failure of exogenously added Shh-N to induce ventral cell types in the presence of teratogenic compounds. Furthermore, although exogenously added Shh-N protein can induce endogenous *Shh* gene expression in neural plate explants (64, 65), we have demonstrated a complete inhibition of response by these teratogens at 2nM Shh-N, a concentration at which there is not induction of floor plate cells and therefore no endogenous *Shh* expression. The inhibitory effects of these compounds are dose-dependent, as demonstrated: (1) by maintenance or even expansion of the Isl-1 intermediate fate at intermediate inhibitor concentrations below those required for complete inhibition; and (2), by the requirement for correspondingly higher concentrations of teratogenic compounds to inhibit the response to increasing levels of Shh-N protein. A further indication of the specificity of these effects is the inability of these compounds to block cell behaviors such as migration, expression of Pax7, or HNK-1, or the response to other inductive signals such as BMP7 at concentrations that completely block the response to *Shh* signaling.

Our studies of sterol synthesis and transport suggest that these compounds are acting as class 2 inhibitors of cholesterol biosynthesis (61). For several reasons, however, simple reduction of cholesterol levels seem unlikely to account for the effects of these compounds on *Shh* signaling. First, the non-teratogenic compound tomatidine also displays potent inhibitory effects on cholesterol synthesis. Second *Shh* signaling in explants is not inhibited by 25-hydroxycholesterol, a hydroxysterol that blocks *de novo* cholesterol biosynthesis (66). We can also rule out an inhibitory role for specific sterol precursors that may accumulate in drug-treated cells, since addition of 25-hydroycholsterol together with inhibitory compounds should eliminate synthesis of sterol precursors yet does not restore the ability to respond to *Shh* signaling (67). An alternative mechanism to simple reduction of cholesterol would be a disruption of intracellular transport.

We have also shown that triparanol, jervine, and cyclopamine are potent inhibitors of PM cholesterol esterification, consistent with their classification as class 2 inhibitors. Consistent with transport disruption as the mechanism of drug action in inhibiting *Shh*

signaling, we have found that several other previously characterized class 2 compounds also are able to inhibit the response to *Shh* signaling in explants (68). Tomatidine, however, also blocks esterification, indicating that general inhibition of this transport pathway is not sufficient for an inhibitory effect on the *Shh* response. We are currently investigating the possibility that this pathway comprises multiple steps that are differentially affected by tomatidine and the teratogenic compounds, and that only those steps not essential for the *Shh* response are affected by tomatidine. The unusual sterols that accumulate in tomatidine-treated cells are associated with peroxisomal sterol metabolism (60), consistent with such a differential effect of tomatidine on intracellular sterol transport.

In light of these drug effects on cholesterol homeostatis, it is interesting to note the presence of a sterol sensing domain (SSD) within Ptc, a key regulator of the Shh signaling pathway (33). The Ptc SSD initially was detected as a region of similarity to the Niemann-Pick C. Disease (NP-C) gene (31, 32). The similarity between Ptc and the NP-C protein extends beyond the five transmembrane spans of the SSD to include all twelve of the proposed transmembrane spans of Ptc. The significance of this sequence homology is not known, and the role of the SSD in NP-C is not clear, although this protein is proposed to regulate intracellular trafficking and loss of its function leads to lysosomal cholesterol accumulation (69). The SSDs of other proteins confer differential responses to high and low levels of intracellular sterols. The HMGCoA reductase enzyme thus displays a 3-5 fold decrease in stability as sterol concentration rise, and this behavior is dependent on the presence of the SSD. The SCAP regulator protein at low (but not at high) sterol concentrations stimulates the activity of the S2P metalloprotease, resulting in cleaveage and activation of the SREBP transcription factor.

Those of the class 2 cholesterol synthesis inhibitors which have been examined appear to increase HMGCoA reductase activity and to stimulate the cleaveage of SREBP. Given the localization of these two proteins to the ER, a likely mechanism for this effect is that disruption of sterol transport from PM to ER by class 2 compounds induces a 'low sterol' state in these ER proteins, despite higher levels of cellular sterols overall. The teratogenic compounds studied here all affect cholesterol synthesis and transport, and it is conceivable that they alter the normal distributions of sterols within intracellular compartments If the function of Ptc is critically dependent upon the sterol concentrations in particular compartment, skewed sterol distributions in this compartment could act to perturb Ptc function via its SSD. One other possibility is that the function of Ptc in *Shh* signaling involves regulation of intracellular transport, as has been suggested for the related NP-C protein. If this were true, the perturbations of transport generated by these

teratogenic compounds might affect the transport functions of Ptc in such a manner as to inhibit Shh signaling.

References for Example 1

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40. Fertile chick eggs (white leghorn) were placed in a humidified incubator at 37.5° C in a rotating tray for 14 hours. The eggs were windowed at the air space and 250 µl of a sonicated 1 mg/ml jervine solution (Leibovitz's L15 medium, Gibco BRL) was applied under the shell membrane. The window was taped and the eggs incubated for an additional 4 days. The embryos were dissected in phosphate buffered saline (PBS, pH 7.2). The heads were removed form the trunk at the superior boarder of the heart and fixed in 3% Glutaraldehyde (EM grade, Polysciences, Inc.) in 0.1M sodium cacodylate (Polysciences, Inc.), 3 mM CaC_{l_2} (pH 7.4) overnight at 4°C. They were washed in 0.1M sodium cacodylate (pH 7.4 placed in 2% osmium tetroxide (Polysciences, Inc.), 0.1M sodium cacodylate (pH 7.4) for 2 hours and washed in water. The samples were then dehydrated in a 50%, 70%, 90% and 100% ethanol series. Samples were critical point dried in liquid CO_2 (CPD Model 10, Polaron), sputtter coated with gold-palladium (Denton Desk II unit) and viewed on an Amray 1810 SEM operated at 20 kV.

41. Hamburger and Hamilton stage 9-10 (8-10 somites) embryos were used for all explant assays. Dissections were carried out in Leibovitz's L15 medium (Gibco BRL). Midline tissue just rostral to Hensen's node and well caudal to the last somite was removed with fine scissors. The neural ectoderm was separated from the lateral plate mesoderm and endoderm with dispase (Boehringer Mannheim, grade II 2.4 U/ml) treatment and then washed in L15. Midline, intermediate and ventral neural plate explants were further dissected with tungsten needles as diagrammed in figures 3A, 6A and 7A. Dissected tissues were transferred to a chambered coverglass (Nunc) in a drop of collagen (vitrogen 100, Collagen Biomaterials, Palo Alto, CA) containing 1X modified Eagle's medium (Gibco BRL) and 24 mM NaH_2CO_3 (final pH 7.4-7.6), and warmed to 37.5°C for 30 minutes (in the absence of CO_2) for gelation. Explants were cultured in 400 µl of F12 Nutrient Mixture (Ham) with glutamine (Gibco BRL), containing N-2 supplement (1X, Gibco BRL) and 100 U/ml penicillin and 100 ug/ml streptomycin in a 5% CO_2, humidified incubator at 37°C. AY 9944, triparanol, jervine, cyclopamine and tomatidine (all from 10mM stocks in 95% ethanol, except AY 9944 which is water soluble), purified Shh-N and BMP 7 were added at the initiation of the cultures. All of the explants were cultured for 40-48 hours except for the intermediate neural plate explants assayed for pax7 repression, which were cultured for 20-22 hours. At the end of the incubation period, explants were fixed in 4.0% formaldehyde (EM grade, Polysciences, Inc.) in PBS for 1 hour at 4°C, washed with PBS and then stained with a secondary antibody for 2 hours at room temperature. Rabbit anti-rat HNF3β (K2) 1:2000, mouse anti-ISL1 (40.2D6) 1:1000, mouse anti-pax7 1:10, mouse anti-rat HNK-1/N-CAM (sigma Biosciences) 1:1000, FITC-conjugated donkey anti-mouse IgG (Jackson ImmunoResearch Laboratories, Inc.) 1:100 and LRSC-conjugated donkey anti-rabbit IgG (Jackson ImmunoResearch Laboratories, Inc.) 1:300 were all diluted in PBTS. The explants were examined with an Olympus IX60 inverted microscope using a planapo objective with a 1.4 numerical aperture. Images were generated by confocal laser scanning microscopy with a cripton-argon laser exciting at 488 and 568 nm with emissions at 450-550 and 550-650 nm and utilizing Oz with Intervission software (Noran) on a Silicon Graphics Inc. platform.
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47. HK293 cells, stably transfected with Shh using the Ecdysone-Inducible Mammalian Expression System (invitrogen), were plated in 6-well culture plates (Flacon, well area 9.6 cm^2) in Dulbecco's modified Eagle's medium (DMEM, Gibco), 10% fetal bovine serum (FBS), 400 µg/ml Zeocin Invitrogen), 2 mM L-glutamine, 100 U/ml Penecillin, 100 µg/ml Stregtomycin, 350 µg/ml G418 (Invitrogen) at 30-40% confluency and grown at 37°C. The following day, the media was changed to one that contained 10% dilapidated serum (K.M. Gibson et al. J. Lipid Res. 31, 515 (1990)) and 1% ITS (Sigma) and otherwise was the same as above. After 24 hours, the cells were induced to express Shh with the addition of 1µM muristerone A (Invitrogen). AY 9944, triparanol, jervine, cyclopamine and tomatidine (all from 10mM stocks in 95% ethanol, except AY 9944 which is water soluble) were added to the cultures at the time of induction. The control cells received 0.475% ethanol to equal the maximum ethanol concentration in the 50 µM steriodal alkaloid treatments. After an additional 24 hours, the culture supernatants were removed and the cells were lysed in the plate with 3X SDS-PAGE cell lysis buffer (3% SDS), diluted two-fold with water and boiled. Lysate samples (and in a separate experiment supernatant samples, for which the data is not shown) were loaded onto SDS-12% polyacrylamide gels for analysis, immunoblotted with primary antibodies for Shh-N and actin (Amersham) and horseradish peroxidase-conjugated secondary antibodies (Jackson ImmunoResearch Laboratories, Inc.), and visualized with a with luminescent substrate (Pierce).

48. Shh processing in transiently transfected cells is ineffecient, with accumulation of 50-80% of Shh protein as unprocessed precursor. Even in these circumstances, we did not observe any effect of jervine, cyclopamine, or tomatidine upon Shh processing efficiency.

49. Unpublished data.

50. The in vitro studies of Hh autoprocessing used a baterially expressed derivative of the Drosophila Hh protein (Porter 96A). The reactions were carried out as described (Porter

96B), except that the sterols and steroidal alkaloids were dried down from an ethanol or chloroform stock and resuspended in a 0.2% Triton-X 100 solution in a bath sonicator prior to addition to the reaction mixture.

51. Other sterols that participate in the reaction with similar efficiency to cholesterol are β-sitosterol, 5-androsten-3β-ol, ergosterol, 4β-hydroxycholesterol, 19-hydroxycholesterol, 20α-hydroxycholesterol, 22(S)-hydroxycholesterol, 22(R)-hydroxycholesterol and 25-hydroxycholesterol. Epicholesterol, cholesterol acetate, α-ecdysone, 20-OH ecdysone and thiocholesterol are unable to participatein the reaction.

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57. Pooled human lymphoblasts were washed with serum free RPMI-1640, then plated in 35 mm microwells in RPMI-1640 with 15% delipidated FBS (Gibson 90) and cultured at 37°C in a 5% CO_2 humidified atmosphere for 12 hours. AY 9944, triparanol, jervine, cyclopamine or tomatidine was then added and the cells were incubated for five days, after which the neutral sterols were extracted and analyzed as described by R.I. Kelley (Clin. Chim. Acta 236, 45 (1995)). Briefly, pelleted cells were saponified at 60°C in 4% (w/v) KOH in 90% ethanol with epicoprostanol as carrier, mixed with an equal volume of water and extracted three times in hexane. The hexane extracts were dried under nitrogen, derivatized with bistrimethylsilyltrifluoroacetamide (BSTFA, Pierce) in pyridine and analyzed by selected ion monitoring gas chromatography/mass-spectrometry (SIM-GC/MS), utilizing a Hewlett Packard (HP) 5890A splitless injection port, a 0.2 mm x 25 m HP-1 methylsilicone (0.33 µm liquid phase) capillary column and a HP 5970A mass selective dector operated in electron impact mode at 70 eV with an ion source temperature of 200°C.

58. For determining their effects on sterol composition, AY 9944 and triparanol were used at 0.5µM and jervine, cyclopamine, and tomatidine were used at 10 µM. Doses lower than these produced more normal sterol profiles; higher doses increased the relative levels of cholesterol precursors but also reduced cell growth during the five day incubation period of this assay.

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67. Addition of 25 µM 25-hydroxycholesterol to explant cultures did not reverse the inhibitory effects of any of the teratogenic compounds.
68. Class 2 cholesterol synthesis inhibitors at the given concentrations block the response of intermediate neural plate explants to 25 nM Shh-N, without affecting signaling by BMP7:U 18666A 0.25 µM, chloroquine 50 µM, imipramine 75 µM, progesterone 20µM.
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Example 2: Essential role for Sonic hedgehog during hair follicle morphogenesis

The hair follicle is a source of epithelial stem cells and site of origin for several types of skin tumors. While it is clear that follicles arise by way of a series of inductive tissue interactions, identification of the signaling molecules driving this process remains a major challenge in skin biology. In this study we report an obligatory role for the secreted morphogen Sonic hedgehog (Shh) during hair follicle development. Hair germs comprising epidermal placodes and associated dermal condensates were detected in both control and Shh -/- embryos, but progression through subsequent stages of follicle development was blocked in mutant skin. The expression of Gli1 and Ptc1 was reduced in Shh -/- dermal condensates and they failed to evolve into hair follicle papillae, suggesting that the adjacent mesenchyme is a critical target for placode-derived Shh. Despite the profound inhibition of hair follicle morphogenesis, late-stage follicle differentiation markers were detected in Shh -/- skin grafts, as well as cultured vibrissa explants treated with cyclopamine to block Shh signaling. Our findings reveal an essential role for Shh during hair follicle morphogenesis, where it is required for normal advancement beyond the hair germ stage of development.

Introduction

Early stages of organogenesis are marked by the appearance of mesenchymal condensates and focal cellular aggregates, or placodes, in adjacent epithelia. This process is driven to completion by a series of inductive signals traveling between epithelial and mesenchymal cell populations which ultimately give rise to the adult structure (reviewed in Gurdon, 1992; Thesleff *et al.*, 1995). In skin appendages such as vibrissae and hair follicles, detailed analysis of tissue recombinants has revealed the existence of at least three morphogenetic signals: the embryonic dermis instructs overlying ectoderm to initiate placode formation; the placode transmits a signal generating a dermal condensate with hair follicle-inductive properties; and the condensate in turn sends a signal to nascent follicle keratinocytes stimulating their proliferation, downgrowth into the developing dermis, and reorganization to form the mature follicle (reviewed in Sengel, 1976; Hardy, 1992). The epithelial and mesenchymal components of the follicle remain in close proximity in mature hair bulbs, where the dermal papilla is surrounded by matrix cells giving rise to at least six phenotypically distinct epithelial cell types in the hair shaft and inner root sheath of the hair follicle. After birth the follicle epithelium cycles through periods of active growth (anagen), followed by regression (catagen) and inactivity (telogen) (reviewed in Cotsarelis, 1997). The morphogenetic program that accompanies the transition from telogen to anagen bears similarities to follicle development during embryogenesis, making this structure a unique model for studying certain aspects of organogenesis in the adult animal. Although a large number of genes have been implicated at various stages of hair follicle development and cycling (reviewed in Rosenquist and Martin, 1996; Sterm *et al,* 1996; Widelitz *et al,* 1997; Millar, 1997), the molecular nature of the inductive signals that underlie the formation of the follicle is largely unknown.

In situ localization of transcripts encoding potential morphogens has revealed focal expression of *Sunic hedgehog (Shh)* in placodes of the epidermis and several other epithelia at early stages of development, with *Ptcl* transcripts encoding a putative Shh receptor also present in adjacent mesenchymal cells (Bitgood and McMahon, 1995; Iseki *et al.*, 1996; Oro *et al.*, 1997; Motoyama *et al.*, 1998). These findings, coupled with the accumulating evidence demonstrating a pivotal role for secreted Hedgehog proteins in a variety of developmental processes (reviewed in Hammerschmidt *et aL,* 1997), led us to examine the potential involvement of this pathway in hair follicle morphogenesis. Since the follicle is a source of cutaneous stem cells and a likely, site of origin for certain epithelial skin cancers (Cotsarelis *et al.*, 1990; Lavker *et al.*, 1993; Rochat *et al.*, 1994; Hansen and Tennant, 1994), understanding the developmental biology of this organ is likely to provide insights relevant to normal skin function as well as wound-healing and

neoplasia, and may shed light on fundamental aspects of organogenesis involving other structures as well.

Methods

Animals and Skin Transplantation

The generation and identification of *Shh* mutant mice was performed as described (Chiang *et al.*, 1996). Embryonic skin was grafted onto the dorsal fascia of nude mice beneath a protective silicone chamber using a modification of a previously-described technique (Dlugosz *et al.*, 1995). The chamber was removed 11-12 days after grafting and tissue harvested for analysis after an additional one to four weeks. Animals were handled in accordance with NIH guidelines.

Immunohistochemistry

Tissue was fixed overnight in Carnoy's or Bouin's solution for detecting keratins (KI, K10, K5, K14, and K 17), loricrin, and filaggrin; fixation with neutral-buffered formalin was used for tissues immunostained with Lef-1, Ki67, and hair keratin (AE13) antibodies. Samples were embedded in paraffin and 8 m sections cut for immunostaining. Immunoreactivity of antigens in formalin-fixed sections was restored by immersing slides in a boiling 0.01M citrate buffer, pH 6, for 10 minutes. The following primary antibodies were used at the indicated dilutions for immunostaining: rabbit anti-keratins K 1, K 10, K5 and K 14 (1:5 00) (Roop *et al.*, 1984), loricrin and filaggrin (1:500) (Roop *et al.*, 1987), supplied by Dr. Stuart Yuspa; rabbit anti-K17 (1: 1000) (McGowan and Coulombe, 1998), provided by Dr. Pierre Coulombe; rabbit anti-Lef- 1 (1:200) (Travis *et al.*, 1991), a gift from Dr. Rudolf Grosschedl; rabbit anti-Ki67, NCL-Ki67p (Novocastra Laboratories, Ltd., Newcastle upon Tyne, UK) (1:200); and mouse monoclonal AE 13 hybridoma supernatant, which recognize type I hair keratins (1:5) (Lynch *et al., 1986),* provided by Dr. Tung-Tien Sun. Tissue sections were incubated with primary antibodies diluted in tris-buffered saline containing 1% bovine serum albumin, typically for 1-2 hours at room temperature. Subsequent immunostaining procedures were performed using peroxidase Vectastain ABC kits (Vector Laboratories, Inc., Burlingame, CA) and 3,3'-diaminobenzidine (Sigma, St. Louis, MO) as a substrate, according to the manufacturers' recommendations. Sections were counterstained with hematoxylin and mounted using Permount (Fisher Scientific, Pittsburgh, PA).

In Situ Hybridization

Non-radioactive RNA *in situ* hybridization was performed on 5 m sections essentially as described (Groves *et al.*, 1995), using previously described sequences for *Glil* (Walterhouse *et al.*, 1993), *Ptcl* (Goodrich *et al.*, 1996), and *BMP-4* (Jones *et al.*, 1991).

Vibrissa Follicle Explants

Vibrissa follicle explants were established using CD- 1 mouse embryos at 13.5 days of gestation according to a previously described protocol (Hirai *et al.*, 1989), with minor midifications. Vibrissa pads were transferred onto Nuclepore filters (13 mm, 8 m pores), and floated on, 2 ml of medium [DMEM (Life Technologies, Gaithersburg, MD) + Ham's F12 medium (Life Technologies) (1:1), with 1% FCS (Intergen, Purchase, NY), penicillin (50 units/ml) and streptomycin (50 gg/ml) (Life Technologies)] in 6-well plates. Similar results were obtained using a DMEM-based medium, without the addition of Ham's F12. Explants were fed fresh medium every two days. Microdissection was performed with the aid of a Nikon SMZ-2T stereomicroscope and photomicrographs were taken using an Olympus OM-4 camera. Cyclopamine was stored at -20 as a 10 mM stock in 95% EtOH.

RNA Isolation and RT-PCR

RNA was obtained by solubilizing individual explants in TriZol (Life Sciences) and isolating as recommended by the manufacturer. cDNA was synthesized using SuperScript II Rnase H reverse transcriptase with random primers (Life Technologies), and RT-PCR performed using the following primers: MHKA1 (318 bp product), (forward 5'-ATCAGAGAATGCCAGGTTGG-3' and reverse 5'-TCATTGAGCACACGGTTCAG-3'); hacl-1 (308 bp product), (forward 5'-TTGTATCTCCACTCCTGCCC.3 and reverse 5'-AGACTCCACAGGTTGGTTGG-3'); profilaggrin (330 bp product), (forward 5-GCTTAAATGCATCTCCAG-3' and reverse 5'-AGTCAGTCCTATTGCAGG-3') (Bickenbach *et al.*, 1995); P actin (421 bp product), (for-ward 5'-TACCACAGGCATTGTGATGGA-3' and reverse 5'CAACGTCACACTTCATGATGG-3') (Walterhouse *et al.*, 1993). The following PCR conditions were used for MHKA1, Hacl-1, and actin: 95 x 3 min "hot start"; 95 x 50 sec, 58 x 30 sec, and 72 x 60 sec for 25 (actin) or 35 cycles (MHKA I and Hacl-1); 72 x 7 min. PCR conditions for profilaggrin primers were as previously described (Bickenbach *et al.*, 1995). Reaction products were run through 1.5% agarose gels and visualized with ethidium bromide.

Results and Discussion

Early stages of hair follicle development appeared similar in control and *Shh* -/- embryos. Hair germs, consisting of clusters of columnar basal keratinocytes protruding into the developing dermis with associated dermal condensates, were detected in the skin of both mutant and control embryos at 15.5 days of gestation (Fig. 8 A,B). Despite the similar morphology of control and Shh-deficient hair germs, a dramatic difference in gene expression patterns was revealed by *in situ* hybridization. The level of *Glil* mRNA was markedly reduced in both the epithelial and mesenchymal components of *Shh* -/- primary hair germs (Fig. 8C,D). In addition, expression of *Ptcl* was reduced in *Shh* mutant hair germs, although some placodes contained levels slightly above background (Fig. 8E,F). These findings are consistent with previous reports identifying Shh as a positive regulator of both *Glil* and *Ptcl* (Marigo and Tabin, 1996; Marigo *et al.*, 1996; Lee *et al.*, 1997; Sasaki *et al.*, 1997), and suggest that Shh is signaling in both the epithelial and mesenchymal cells of the developing follicle. In contrast to *Glil* and *Ptcl*, *BMP-4* mRNA was clearly detectable in condensates of mutant and control embryos (Fig. 8G,H), arguing against a requirement for Shh in the induction of *BMP-4* expression. Thus, although Shh is not required for the initiation of hair follicle development, primary hair germs that arise in Shh mutant skin are deficient in the expression of at least some Shh target genes.

In control embryos, the interval between E15.5 and E17.5 is marked by rapid proliferation and downgrowth of the follicle into the developing dermis, accompanied by a several-fold increase in the mass of the follicle epithelium and reorganization into distinct cellular compartments. In the most mature follicles, keratinocytes in the most peripheral cell layer, which give rise to the outer root sheath in the mature follicle, have assumed a columnar arrangement perpendicular to the long axis of the developing follicle; cells located centrally are without a definite orientation at this stage but will eventually be replaced by the three concentric layers of inner root sheath cells and the three cell types comprising the hair shaft; and the epithelial cells of the deepest portion of the follicle, the future hair bulb, have surrounded what. is at this stage a well-defined cluster of mesenchymal cells, the dermal papilla (Fig. 9A, arrow). Even the less mature follicles exhibit an organized "cap" of mesenchymal cells at their invaginating tips (Fig. 9A, arrowheads). In striking contrast, hair follicles in skin from mutant embryos at E 17.5 failed to develop past the hair germ stage seen at E 15.5 (Fig. 9B). Although the follicle epithelium was most obviously affected due to its lack of growth, organizing dermal condensates and dermal papillae were conspicuously absent in mutant skin. These results are consistent With the idea that epidermis-derived Shh (Bitgood and McMahon, 1995;

Iseki *et al.*, 1996; Oro *et al.*, 1997; Motoyama *et al.*, 1998) functions as a paracrine signal regulating development of the mesenchymal component of the hair follicle. Inhibition of follicle formation is not likely to be due to a general disruption of skin development since epidermal morphogenesis, marked by the appearance of granular and cornified cell layers, took place by E 17.5 in both control and mutant embryos (Fig. 9A,B).

Additional studies were performed to determine whether Shh influenced the expression of epithelial differentiation markers in embryonic skin. Keratinocytes in developing hair follicles can be distinguished by a relative deficiency of K5 and K14, keratins that are abundant in surrounding epidermal basal cells (Kopan and Fuchs, 1989; Byrne *et al.*, 1994). Immunohistochemical staining of E17.5 embryos revealed greatly reduced or undetectable levels of K14 in a sub-population of cells comprising the normal follicles in control embryos as well as the primordial follicles seen in *Shh* -/- embryos (Fig. 9C,D; arrows). Moreover, K17, which is normally not detected in interfollicular epidermis but is expressed in developing and mature hair follicles (Panteleyev *et al.*, 1997; McGowan and Coulombe, 1998), was localized to the follicular epithelium in both control and mutant skin (Fig. 9E,F). Thus, although morphogenesis of hair follicles in *Shh* -/- skin fails to progress past the hair germ stage, these structures contain epithelial cells that have initiated a terminal differentiation program characteristic of developing follicle keratinocytes. Consistent with the morphological findings in Figs. 9A and B, the expression level of epidermal-specific differentiation markers (keratins 1 and 10, loricrin, and filaggrin) in *Shh* -/- skin was similar to or greater than in control epidermis, based on immunchistochernical. staining (data not shown).

Since *Shh* -/- mice are not viable, post-natal analysis of mutant skin was performed following grafting onto nude mice. Whereas skin from control mice produced abundant pigmented hairs, transplanted *Shh* -/skin failed to generate detectable hairs but exhibited a pigmented graft site, consistent with the strain of donor skin (Fig. 10A). The histology of control skin grafts revealed the typical structures seen in normal mouse skin, including numerous hair follicles and sebaceous glands (Fig. 10B). In striking contrast, mutant skin failed to produce normal-appearing follicles, hair shafts, or sebaceous glands, but in some cases (3 of a total of 7 *Shh* -/- grafts), exhibited a thickened epidermis with focal areas of hyperkeratosis (Fig. 10C). Conspicuous aggregates of basophilic cells with scant cytoplasm were detected at the dermal-epidermal junction in these mutant grafts (Fig. 10C, arrows). Interestingly, the morphology of cells in the Shh-deficient keratinocyte aggregates was reminiscent of cells in control hair bulbs, and additional analyses revealed biochemical similarities. Cells in these aggregates were unreactive with K5 antibodies (Fig. 10D, arrows), exhibited abundant nuclear Lef-1 expression (Fig. 10 E) (Zhou *et al.*,

1995), and contained a high proportion of proliferating cells detected by Ki67 immunostaining (data not shown). Interestingly, short columnar structures resembling abortive hair shafts were associated with some of the *Shh* mutant keratinocyte aggregates. Moreover, these structures expressed hair-specific keratin (Fig. 10F), indicating that an advanced stage in the follicle differentiation program was achieved despite a dramatic disruption of normal morphogenesis. Rarely, a small cluster of mesenchymal cells was seen associated with the base of a keratinocyte aggregate, as illustrated in Fig. 10E, where these cells immunostain with Lef-1 antibody These findings suggest that a rudimentary dermal papilla is present in at least some of the hair germs seen in *Shh* mutant grafts.

To better define the temporal requirement for Shh during follicle development, tissue culture studies were performed using cyclopamine (GaTield and Keeler, 1996), which has recently been shown to block Shh signaling in neural plate explants (Cooper *et al.*, 1998; Incardona *et al.*, 1998). Explants were established using vibrissa pads obtained from mice at 13.5 days of gestation (Hirai *et al.*, 1989). When grown for six to eight days in culture, explants undergo robust morphogenesis resulting in the formation of elongated, grossly normal-appearing vibrissa follicles (Fig. 11A). These follicles contained hair shafts and expressed genes encoding mouse hair keratin A I (MHKA 1) (Kaytes *et al.*, 199 1) and a hair cortex-specific marker Hacl- 1 (Huh *et al.*, 1994), detected by RT-PCR (Fig. 11B). Treatment of explants with cyclopamine results in striking inhibition of morphogenesis, indicating that Shh signaling is required during or shortly after the hair germ stage of vibrissa. follicle development (Fig. 11C). In keeping with our results obtained using Shh mutant skin, hair-specific transcripts are detected in cyclopamine-treated grafts (Fig. 11B) despite their altered development, providing further support for the notion that biochemical differentiation of the follicle is not necessarily coupled to its morphogenesis. Both control and cyclopamine-treated explants accumulate profilaggrin mRNA, indicating that disruption of Shh signaling does not inhibit epidermal differentiation.

Collectively, the results of our studies reveal an obligatory role for Shh in the progression of hair follicle morphogenesis past the hair germ stage of development. The reduced expression of *Ptc1* and *Gli1* in *Shh* -/- dermal condensates, coupled with their failure to evolve into recognizable dermal papillae, argue that Shh is involved in regulating development of the mesenchymal component of the hair follicle, although a requirement for Shh signaling in the epithelial component of the follicle cannot be excluded. In the absence of dermal papillae normal hair follicle morphogenesis does not proceed, underscoring the critical influence these cells have on growth and remodeling of developing follicle epithelium (Jahoda *et al.*., 1984; Weinberg *et al.*., 1993). Interestingly, biochemical differentiation of the follicle can take place in the absence of normal

morphogenesis, implying that these two processes are regulated independently in this organ. Additional experiments will be required to formally define which component of the developing follicle is functionally impaired in *Shh* -/- embryos, and to determine whether Shh has additional roles at later stages of follicle development or during hair cycling. We anticipate that these studies may ultimately help explain how constitutive activation of the Shh signaling pathway in keratinocytes contributes to the formation of basal cell carcinoma (Johnson *et al.*, 1996; Hahn *et al.*, 1996; Oro *et al.*, 1997; Fan *et al.*, 1997; Xie *et al.*, 1998).

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Example 3: Rescue of ptc loss-of-function phenotype

Based on the results presented above, we have attempt to determine the site in the *Shh* signaling pathway at which cyclopamine operates, and therefor better understand the

spectrum of tumors caused by Shh pathway-activating lesions that could potentially be treated with this compound.

These studies involve the use of mouse embryonic fibroblasts (MEFs) that were generated by trypsin digestion of E8.5 embryos from patched (*ptc*) +/- matings. The mouse *ptc* gene was disrupted by homologous recombination in which part of exon1 and all of exon 2 were replaced with the bacterial *lacZ* gene (Goodrich *et al*, (1997) Science 277:1109). As *Ptc* protein suppresses Shh signaling, a loss of its function activates the Shh signaling pathway. Shh signaling, through a cascade of events, is mediated by the Gli transcription factors. One of the target genes of Shh signaling is *ptc*, through Gli-binding sites in the *ptc* promoter region, and this serves as a feedback mechanism for down regulation of signaling. Thus, in these *ptc* -/- embryos, the Shh signaling pathway is activated in many tissues, and the *lacZ* gene product β-galactosidase is expressed in all of those tissues as a report of pathway activation.

We obtained these MEFs to determine whether cyclopamine acts on Ptc or another component of the cascade to inhibit Shh signaling. If the target of cyclopamine is Ptc, then one would expect that when the Shh pathway is activated by the loss of ptc function, it could no longer be inhibited by cyclopamine. Figure 12 demonstrates that the Shh signaling pathway can be activated in these fibroblasts in cell culture, and that the level of β-galactosidase activity does reflect the degree of pathway activation. The MEF line 23-4 is heterozygous for *ptc-lacZ*, and thus contains one functional ptc allele capable of maintaining a repressed state of the pathway, but will express *lacZ* when the pathway is activated by addition of Shh protein (see Figure 12).

In contrast, the β-galactosidase activity in MEFs homozygous for *ptc-lacZ*, (cell line 23-1) is markedly elevated, because in these cells the pathway is constitutively activated by the loss of a functional *ptc* allele (Figure 13). When these cells are cultured with cyclopamine, β-galactosidase activity is decreased, indicating that when the Shh signaling pathway is unregulated by Ptc repression, it is still sensitive to cyclopamine inhibition. The reduction of β-galactosidase activity appears to result from the specific inhibition of Shh signaling, rather than from cell toxicity because enzymatic activity is normalized to whole protein content of the sample. Also, the reduction of β-galactosidase activity can be obtained with exposure to cyclopamine over a period of time that is shorter than the average cell cycle, and so does not appear to be due solely to an inhibition of cell proliferation (Figure 14).

A final indication that this represents specific inhibition of Shh signaling is that it cannot be achieved with a non-inhibitory, but structurally related compound tomatidine (Figure 15).

All of the references cited above are hereby incorporated by reference herein.

Equivalents

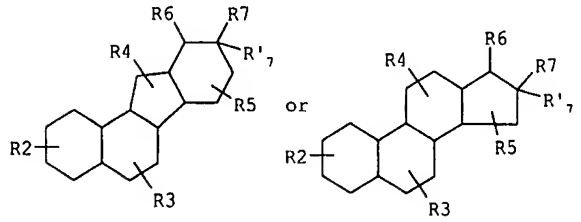
Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. Such equivalents are intended to be encompassed by the following claims.

Claims

1. A method for inhibiting paracrine and/or autocrine signals produced by a hedgehog proteins comprising contacting a cell senstive to the hedgehog protein with a hedgehog antagonist in a sufficient amount to reduce the sensitivity of the cell to the hedgehog protein, wherein the hedgehog antagonist is a organic molecule having a molecule weight less than 750 amu.

2. A method for inhibiting an altered growth state of a cell having a ptc loss-of-function phenotype or a smoothened gain-of-function phenotype, comprising contacting the cell with a *ptc* agonist in a sufficient amount to inhibit the altered growth state, wherein the *ptc* agonist is a organic molecule having a molecule weight less than 750 amu.

3. The method of claim 1 or 2, wherein hedgehog antagosit is a the steroidal alkaloid represented in the general forumlas (I), or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula I

wherein, as valence and stability permit,

R_2, R_3, R_4, and R_5, represent one or more substitutions to the ring to which each is attached, for each occurrence, independently represent hydrogen, halogens, alkyls, alkenyls, alkynyls, aryls, hydroxyl, =O, =S, alkoxyl, silyloxy, amino, nitro, thiol, amines, imines, amides, phosphoryls, phosphonates, phosphines, carbonyls, carboxyls, carboxamides, anhydrides, silyls, ethers, thioethers, alkylsulfonyls, arylsulfonyls, selenoethers, ketones, aldehydes, esters, or $-(CH_2)_m-R_8$;

R_6, R_7, and R'_7, are absent or represent, independently, halogens, alkyls, alkenyls, alkynyls, aryls, hydroxyl, =O, =S, alkoxyl, silyloxy, amino, nitro, thiol, amines, imines, amides, phosphoryls, phosphonates, phosphines; carbonyls, carboxyls, carboxamides, anhydrides, silyls, ethers, thioethers, alkylsulfonyls, arylsulfonyls, selenoethers, ketones, aldehydes, esters, or $-(CH_2)_m-R_8$, or

R_6 and R_7, or R_7 and R'_7, taken together form a ring or polycyclic ring, e.g., which is susbstituted or unsubstituted,

with the proviso that at least one of R_6, R_7, or R'_7 is present and includes a primary or secondary amine;

R_8 represents an aryl, a cycloalkyl, a cycloalkenyl, a heterocycle, or a polycycle; and

m is an integer in the range 0 to 8 inclusive.

4. The method of claim 3, wherein:

R_2 and R_3, for each occurrence, is an -OH, alkyl, -O-alkyl, -C(O)-alkyl, or -C(O)-R_8;

R_4, for each occurrence, is an absent, or represents -OH, =O, alkyl, -O-alkyl, -C(O)-alkyl, or -C(O)-R_8;

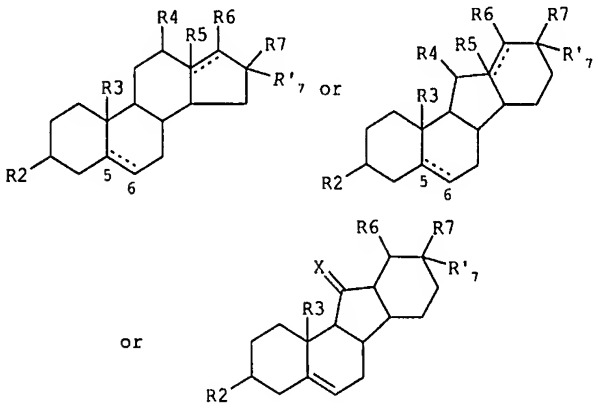
R_6, R_7, and R'_7 each independently represent, hydrogen, alkyls, alkenyls, alkynyls, amines, imines, amides, carbonyls, carboxyls, carboxamides, ethers, thiocthers, esters, or -$(CH_2)_m$-R_8, or

R_7, and R'_7 taken together form a furanopiperidine, such as perhydrofuro[3,2-b]pyridine, a pyranopiperidine, a quinoline, an indole, a pyranopyrrole, a naphthyridine, a thiofuranopiperidine, or a thiopyranopiperidine

with the proviso that at least one of R_6, R_7, or R'_7 is present and includes a primary or secondary amine;

R_8 represents an aryl, a cycloalkyl, a cycloalkenyl, a heterocycle, or a polycycle, and preferably R_8 is a piperidine, pyrimidine, morpholine, thiomorpholine, pyridazine,

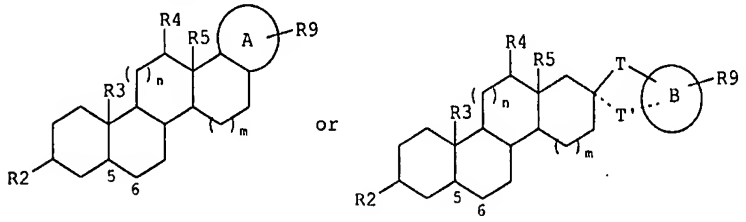
5. The method of claim 1 or 2, wherein the hedgehog antagonist is a steroidal alkaloid represented in the general formula (II), or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula II

wherein R_2, R_3, R_4, R_5, R_6, R_7, and R'_7 are as defined above, and X represents O or S, though preferably O.

6. The method of claim 1 or 2, wherein the steroidal hedgehog antagonist is a alkaloid represented in the general formula (III), or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula III

wherein

R_2, R_3, R_4, R_5 and R_8 are as defined above;

A and B represent monocyclic or polycyclic groups;

T represent an alkyl, an aminoalkyl, a carboxyl, an ester, an amide, ether or amine linkage of 1-10 bond lengths;

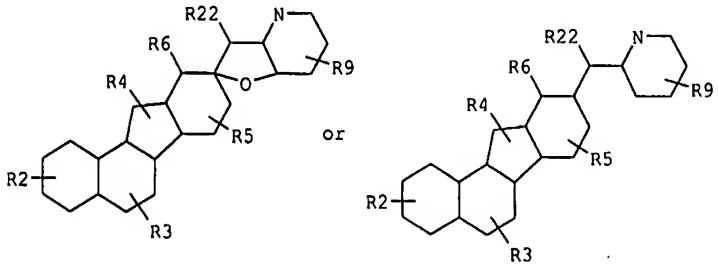
T' is absent, or represents an alkyl, an aminoalkyl, a carboxyl, an ester, an amide, ether or amine linkage of 1-3 bond lengths, wherein if T and T' are present together, than T and T' taken together with the ring A or B form a covelently closed ring of 5-8 ring atoms;

R9 represent one or more substitutions to the ring A or B, which for each occurrence, independently represent halogens, alkyls, alkenyls, alkynyls, aryls, hydroxyl, =O, =S, alkoxyl, silyloxy, amino, nitro, thiol, amines, imines, amides, phosphoryls, phosphonates, phosphines, carbonyls, carboxyls, carboxamides, anhydrides, silyls, ethers, thioethers, alkylsulfonyls, arylsulfonyls, selenoethers, ketones, aldehydes, esters, or $-(CH_2)_m-R_8$; and

n and m are, independently, zero, 1 or 2;

with the proviso that A and R_9, or T, T' B and R_9, taken together include at least one primary or secondary amine.

7. The method of claim 1 or 2, wherein the hedgehog antagonist is a steroidal alkaloid represented in the general formula (IV), or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



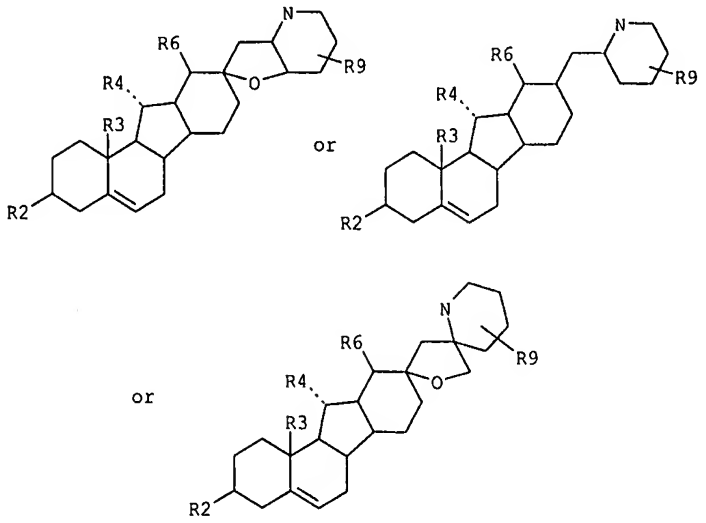
Formula IV

wherein

R_2, R_3, R_4, R_5, R_6 and R_9 are as defined above;

R_{22} is absent or represents an alkyl, an alkoxyl or -OH.

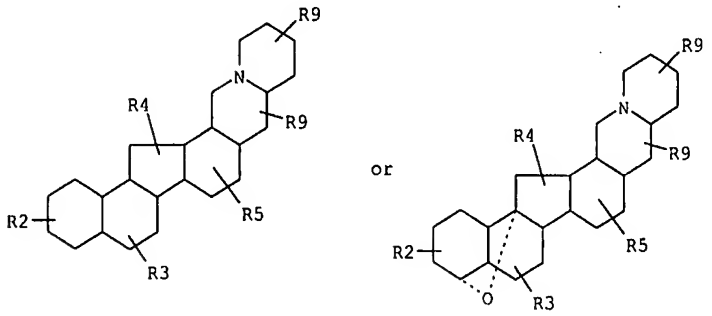
8. The method of claim 1 or 2, wherein the hedgehog antagonist is a steroidal alkaloid represented in the general formula (V) or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula V

wherein R_2, R_3, R_4, R_6 and R_9 are as defined above;

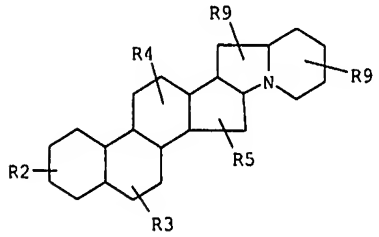
9. The method of claim 1 or 2, wherein the hedgehog antagonist is a steroidal alkaloid represented in the general formula (VI), or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula VI

wherein R_2, R_3, R_4, R_5 and R_9 are as defined above;

10. The method of claim 1 or 2, wherein the hedgehog antagonist is a steroidal alkaloid represented in the general formula (VII) or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula VII

wherein R_2, R_3, R_4, R_5 and R_9 are as defined above.

11. The method of any of claims 3-10, wherein the steroidal alkaloid does not substantially interfere with the biological activity of such steroids as aldosterone, androstane, androstene, androstenedione, androsterone, cholecalciferol, cholestane, cholic acid, corticosterone, cortisol, cortisol acetate, cortisone, cortisone acetate, deoxycorticosterone, digitoxigenin, ergocalciferol, ergosterol, estradiol-17-α, estradiol-17-β, estriol, estrane, estrone, hydrocortisone, lanosterol, lithocholic acid, mestranol, β-methasone, prednisone, pregnane, pregnenolone, progesterone, spironolactone, testosterone, triamcinolone and their derivatives.

12. The method of any of claims 3-10, wherein the steroidal alkaloid does not specifically bind a nuclear hormone receptor.

13. The method of any of claims 3-10, wherein the steroidal alkaloid does not specfically bind estrogen or testerone receptors.

14. The method of any of claims 3-10, wherein the steroidal alkaloid has no estrogenic activity at therapeutic concentrations.

15. The method of any of claims 1-10, wherein the hedgehog antagonist inhibits hedgehog-mediated signal transduction with an ED_{50} of 1mM or less.

16. The method of any of claims 1-10, wherein the hedgehog antagonist inhibits hedgehog-mediated signal transduction with an ED_{50} of 1μM or less.

17. The method of any of claims 1-10, wherein the steroidal alkaloid inhibit hedgehog-mediated signal transduction with an ED_{50} of 1nM or less.

18. The method of claims 1 or 2, wherein the cell is contacted with the hedgehog antagonist *in vitro*.

19. The method of claims 1 or 2, wherein the cell is contacted with the hedgehog antagonist *in vivo*.

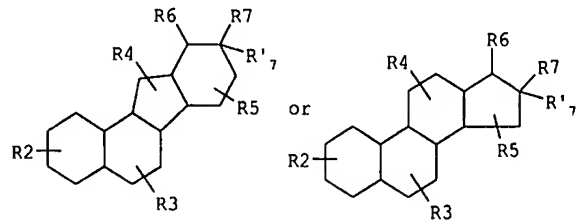
20. The method of claim 1 or 2, wherein the hedgehog antagonist is administered as part of a therapeutic or cosmetic application.

21. The method of claim 19 or 20, wherein the hedgehog antagonist is administered to treat a condition selected from the group consisting of regulation of neural tissues, bone and cartilage formation and repair, regulation of spermatogenesis, regulation of smooth muscle, regulation of lung, liver and other organs arising from the primative gut, regulation of hematopoietic function, regulation of skin and hair growth, etc.

22. The method of any of claims 1-7, wherein the hedgehog antagonist is applied as a topical formulation to skin in order to inhibit aberrant proliferation of epithelial cells.

23. The method of any of clams 1-17 or 22, wherein the hedgehog antagonist is administered to patient to inhibit growth of a basal cell carcinoma.

24. A pharmaceutical preparation comprising steroidal alkaloid is represented in the general forumlas (I), or unsaturated forms thereof and/or seco-, nor- or homo-derivatives thereof:



Formula I

wherein, as valence and stability permit,

R_2, R_3, R_4, and R_5, represent one or more substitutions to the ring to which each is attached, for each occurrence, independently represent hydrogen, halogens, alkyls, alkenyls, alkynyls, aryls, hydroxyl, =O, =S, alkoxyl, silyloxy, amino, nitro, thiol, amines, imines, amides, phosphoryls, phosphonates, phosphines, carbonyls, carboxyls, carboxamides, anhydrides, silyls, ethers, thioethers, alkylsulfonyls, arylsulfonyls, selenoethers, ketones, aldehydes, esters, or $-(CH_2)_m-R_8$;

R_6, R_7, and R'_7, are absent or represent, independently, halogens, alkyls, alkenyls, alkynyls, aryls, hydroxyl, =O, =S, alkoxyl, silyloxy, amino, nitro, thiol, amines, imines, amides, phosphoryls, phosphonates, phosphines, carbonyls, carboxyls, carboxamides, anhydrides, silyls, ethers, thioethers, alkylsulfonyls, arylsulfonyls, selenoethers, ketones, aldehydes, esters, or $-(CH_2)_m-R_8$, or

R_6 and R_7, or R_7 and R'_7, taken together form a ring or polycyclic ring, e.g., which is susbstituted or unsubstituted,

with the proviso that at least one of R_6, R_7, or R'_7 is present and includes a primary or secondary amine;

R_8 represents an aryl, a cycloalkyl, a cycloalkenyl, a heterocycle, or a polycycle; and

m is an integer in the range 0 to 8 inclusive.

25. The preparation of claim 24, formulated for topical application.

26. A process for manufacturing a medicament comprising formulating a steroid alkaloid inhibitor of a hedgehog signal transduction pathway in a pharmaceutically acceptable excipient to from a sterile medicament for preventing growth of cells having an aberrant activation hedgehog pathway.

WO 99/52534 PCT/US99/07811

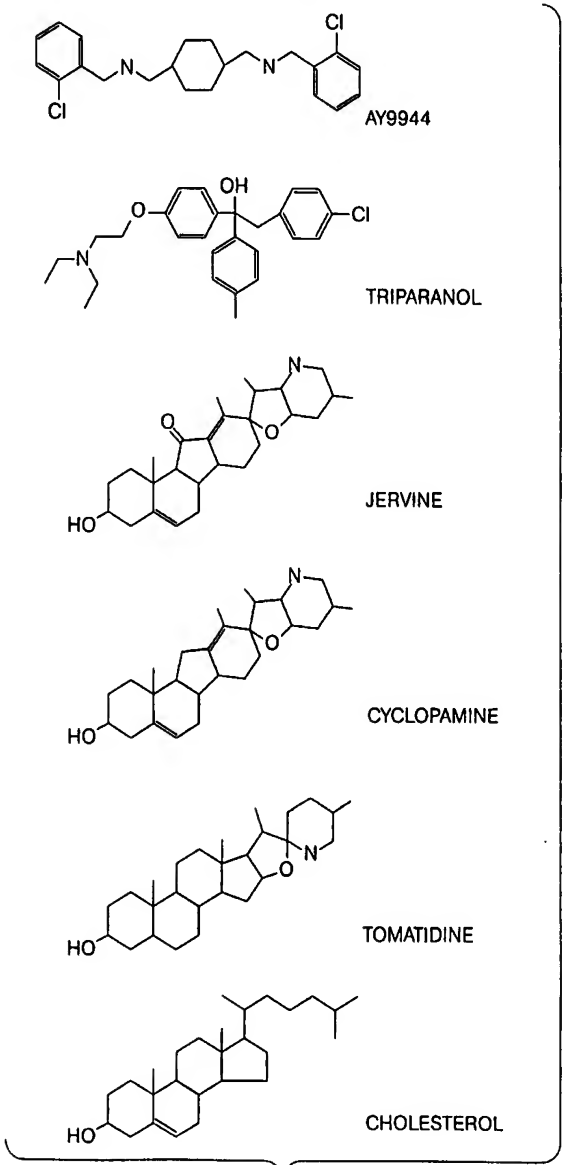


Fig. 1

Fig. 2A

Fig. 2B

Fig. 2C

Fig. 2D

Fig. 2E

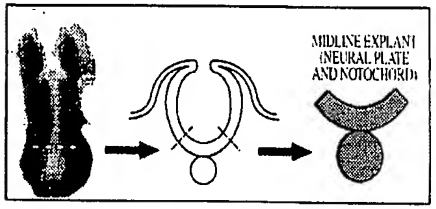


Fig. 3A

Fig. 3B

Fig. 3C

Fig. 3D

Fig. 3E

Fig. 3F

Fig. 3G

Fig. 3H

Fig. 3I

Fig. 3J

Fig. 3K

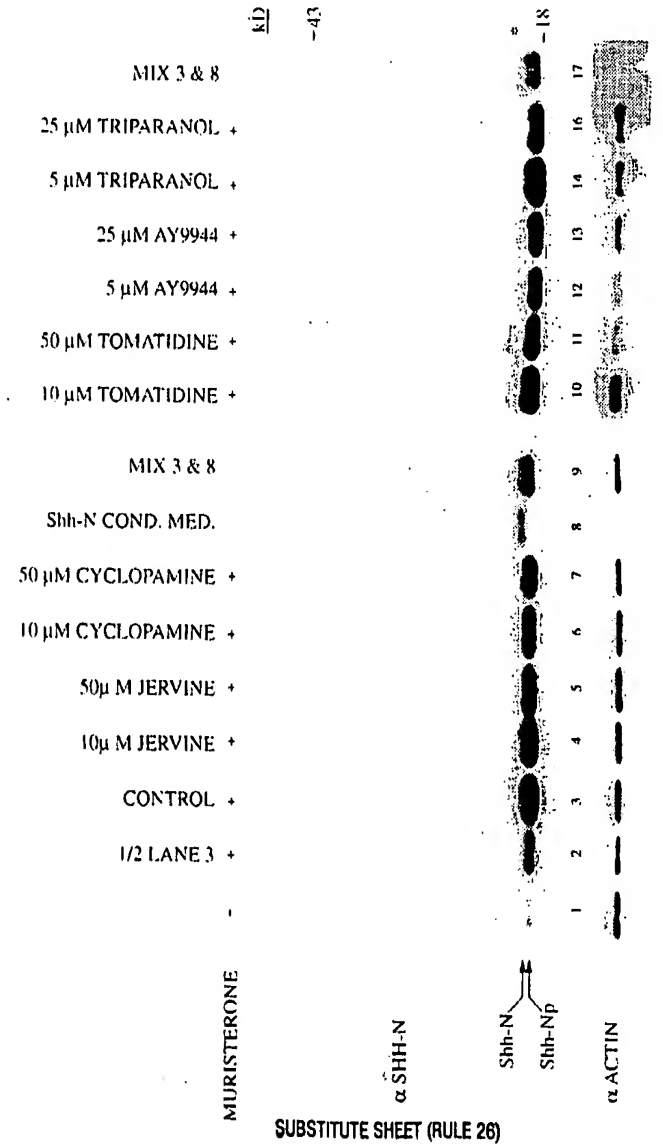


Fig. 4

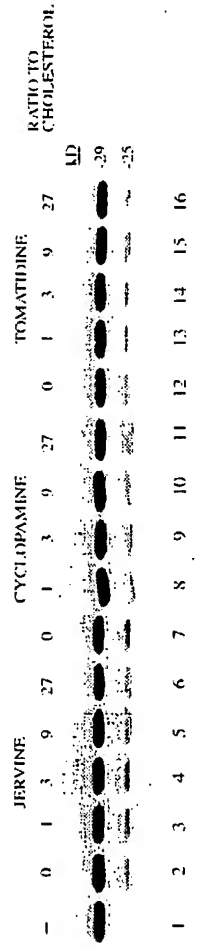


Fig. 5A

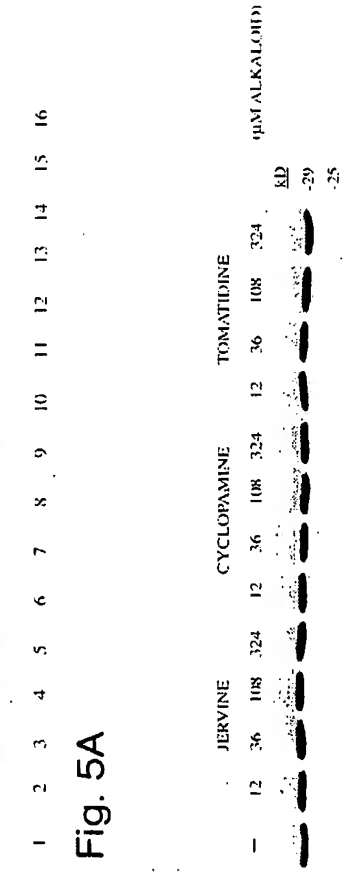


Fig. 5B

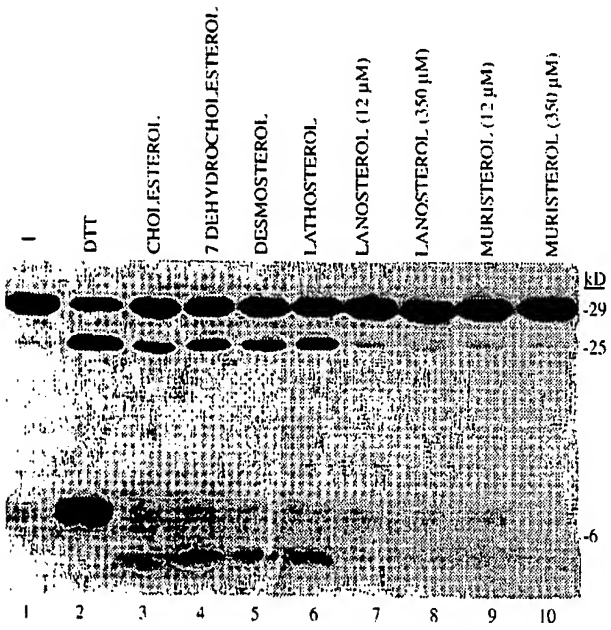


Fig. 5C

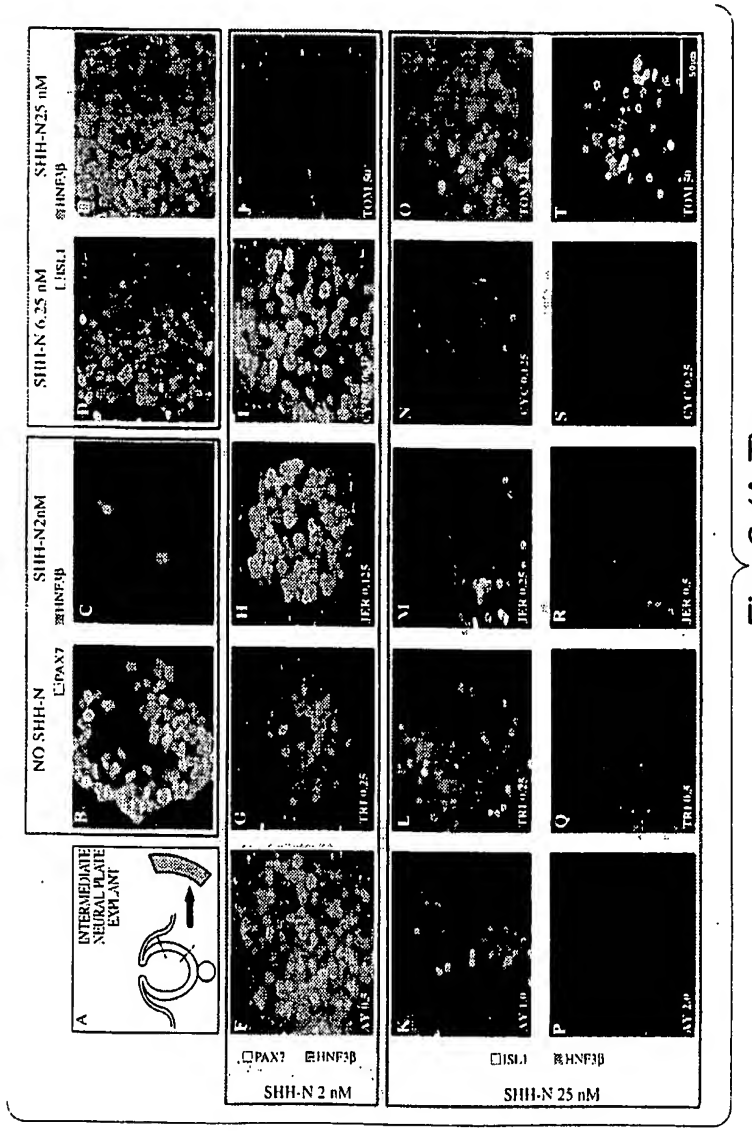


Fig. 6 (A-T)

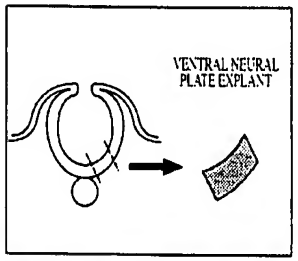


Fig. 7A

Fig. 7B

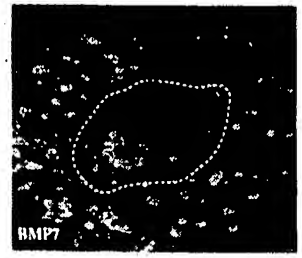


Fig. 7C

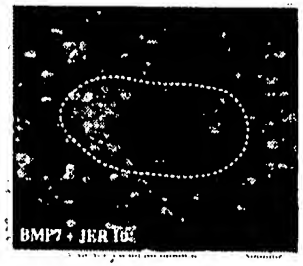


Fig. 7D

Fig. 8A

Fig. 8B

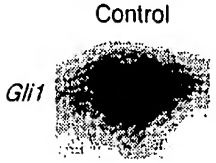


Fig. 8C

Fig. 8D

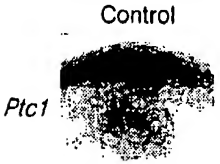


Fig. 8E

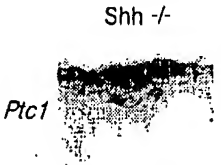


Fig. 8F

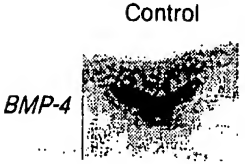


Fig. 8G

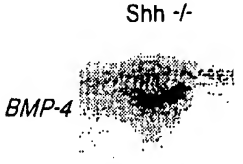


Fig. 8H

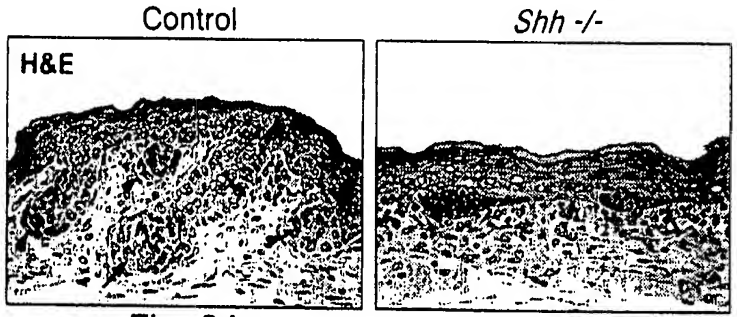


Fig. 9A Fig. 9B

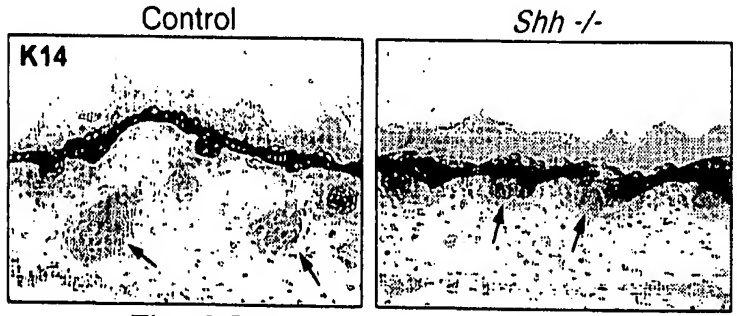


Fig. 9C Fig. 9D

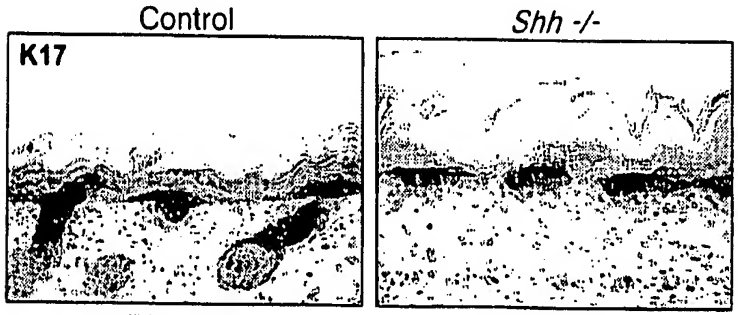


Fig. 9E Fig. 9F

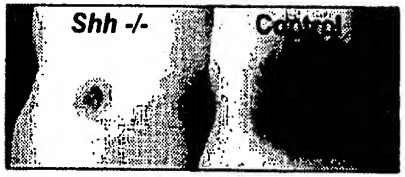


Fig. 10A

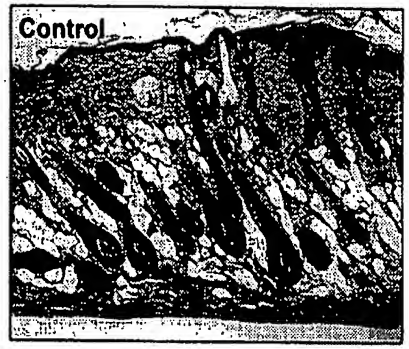


Fig. 10B

Fig. 10C

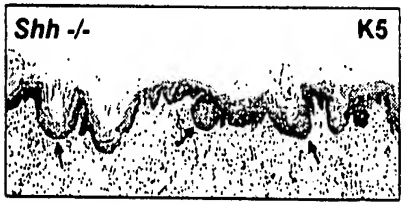


Fig. 10D

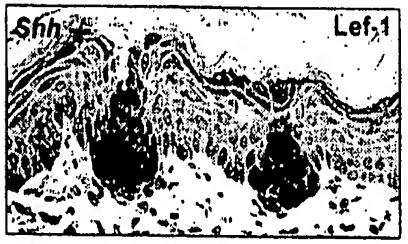


Fig. 10E

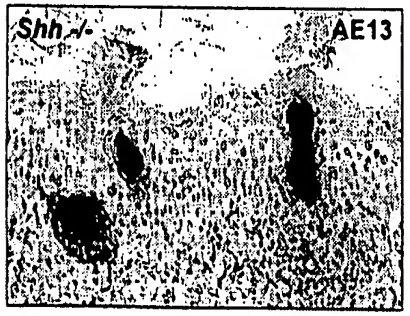


Fig. 10F

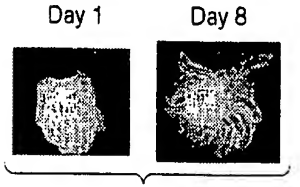


Fig. 11A

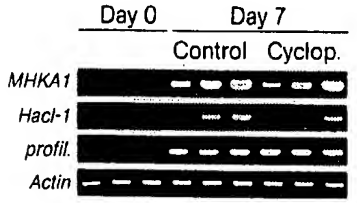


Fig. 11B

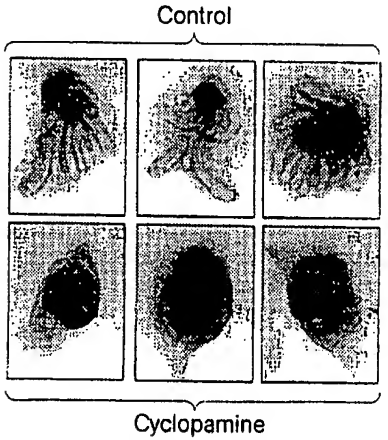


Fig. 11C

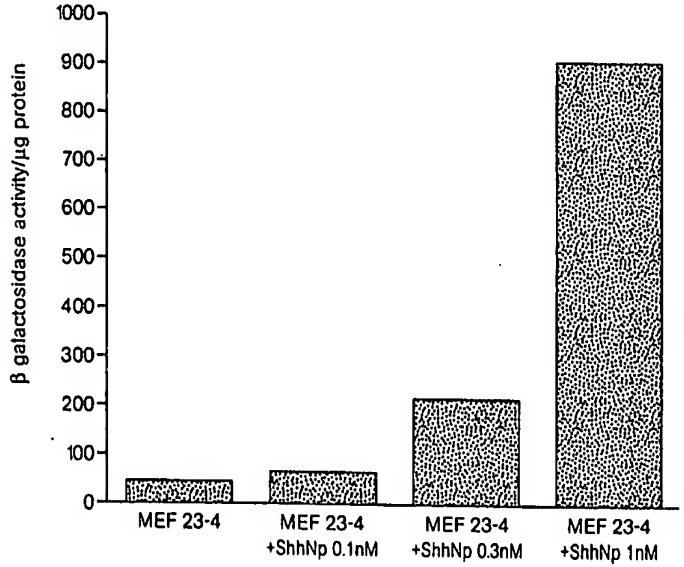


Fig. 12

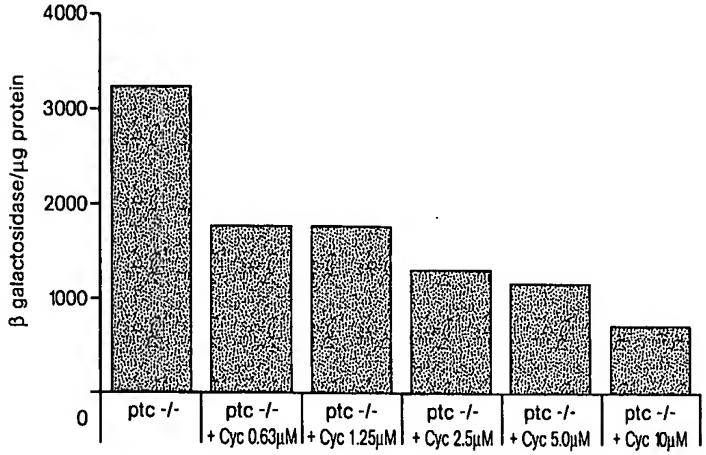


Fig. 13

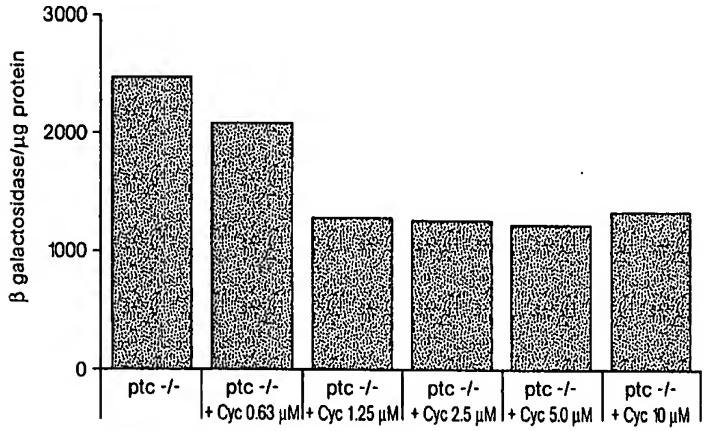


Fig. 14

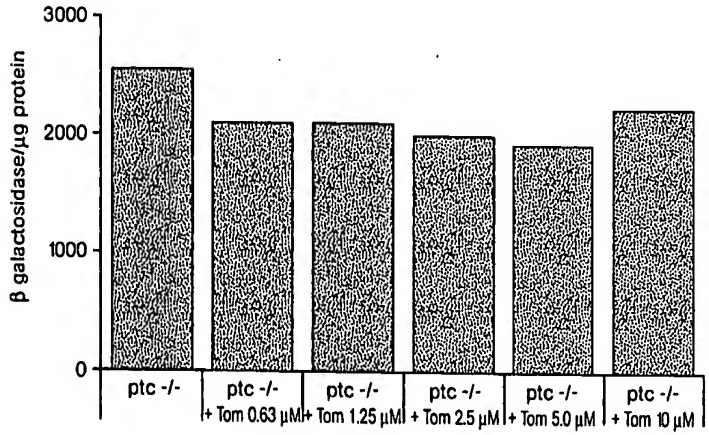


Fig. 15

INTERNATIONAL SEARCH REPORT

Inte. onal Application No
PCT/US 99/07811

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 A61K31/585 A61K31/58

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 A61K C07J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	WO 98 58650 A (UNIVERSITY OF UTAH RESEARCH FOUNDATION) 30 December 1998 (1998-12-30) claims 1-17 page 9, line 3 - line 27	1,2, 10-20, 24,26
X	EP 0 020 029 A (ARUBA (QLD.) PTY. LTD.) 10 December 1980 (1980-12-10) the whole document	1,2, 10-26
X	WO 91 10743 A (CURA NOMINEES PTY LTD) 25 July 1991 (1991-07-25) claims 2-4,8-18	1,2, 10-26
A	US 3 673 175 A (G. SCHRAMM) 27 June 1972 (1972-06-27) the whole document	1-26

-/--

[X] Further documents are listed in the continuation of box C. [X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
5 August 1999	13/08/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Siatou, E

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Inta. .onal Application No
PCT/US 99/07811

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 16, no. 581 (C-1012), 21 December 1992 (1992-12-21) & JP 04 230696 A (SANWA SHIYOUYAKU KK), 19 August 1992 (1992-08-19) abstract	1-26
A	GB 1 227 728 A (OSTERREICHISCHE STICKSTOFFWERKE AG) 7 April 1971 (1971-04-07) the whole document	1-26
A	EP 0 375 349 A (SMITHKLINE BEECHAM CO) 27 June 1990 (1990-06-27) the whole document	1-26

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 99/07811

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [X] Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
Remark: Although claim(s) 1-23
is(are) directed to a method of treatment of the human/animal body, the search has been carried out and based on the alleged effects of the compound/composition.

2. [X] Claims Nos.: 1-2(PARTIALLY)
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest.

[ ] No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (1)) (July 1998)

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box I.2

Claims Nos.: 1-2 (partially)

Present claims 1-2 relate to a method defined by reference to a desirable characteristic or property, namely a hedgehog antagonist or a ptc agonist for inhibiting altered growth state or autocrine/paracrine signals having a molecular weight of less than 750amu.
The claims cover all methods having this characteristic or property, whereas the application provides support within the meaning of Article 6 PCT and/or disclosure within the meaning of Article 5 PCT for only a very limited number of such methods. In the present case, the claims so lack support, and the application so lacks disclosure, that a meaningful search over the whole of the claimed scope is impossible. Independent of the above reasoning, the claims also lack clarity (Article 6 PCT). An attempt is made to define the product/compound/method/apparatus by reference to a result to be achieved. Again, this lack of clarity in the present case is such as to render a meaningful search over the whole of the claimed scope impossible. Consequently, the search has been carried out for those parts of the claims which appear to be clear, supported and disclosed, namely those parts relating to the methods using the compounds defined by the formulas (I)-(VII)

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No PCT/US 99/07811

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